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SEISMIC REFRACTION DATA PROCESSING SOFTWARE: SEISMO VERSION 2.7

by

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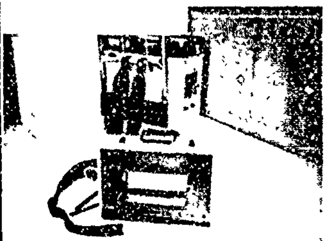

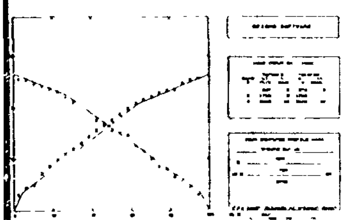

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A software package entitled "SEISMO" has been developed to perform seismic refraction data reduction, interpretation, and presentation. The software package will do both forward and inverse modeling of refraction data, calculation of results, display of results, and final report figure presentation of results. The basic concepts of seismic refraction surveying and the procedures for forward and inverse modeling of refraction data are presented. In addition, several case histories of data processed with the software package are presented.

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PREFACE

This report describes the user guidelines for implementing the seismic refraction data analysis and presentation software SEISMO. This user's guide contains information about data input, calculation procedures, output, graphics, and presentation. Two appendices are included that explain the concepts of the two types of modeling available with seismic refraction data, inverse and forward modeling. Three examples are included in a third appendix to illustrate the material in this text.

Partial funding for development of the program came from Headquarters, US Army Corps of Engineers (HQUSACE), and part came from the US Army Engineer Topographic Laboratory (ETL) under work performed by the Water Detection Response Team (WDRT). Funding from the HQUSACE was provided to make program improvements, corrections, modifications, and documentation under the Numerical Modeling Maintenance Program. Funding from ETL was provided to establish a program that could be used by the WDRT.

SEISMO was initially developed by Mr. D. E. Yule with assistance from Mr. M. K. Sharp. Corrections, modifications, and improvements were performed by Mr. Sharp and Mr. Yule. This report was prepared by Mr. Sharp.

The project was accomplished under the general supervision of Dr. William F. Marcuson III, Chief, Geotechnical Laboratory, US Army Engineer Waterways Experiment Station. Direct supervision was provided by Mr. J. R. Curro, Chief, Engineering Geophysics Branch, GL, Dr. Mary Ellen Hynes, Chief, Earthquake Engineering and Seismology Branch, GL, and Dr. A. G. Franklin, Chief, Earthquake Engineering and Geosciences Division, GL.

COL Larry B. Fulton, EN, was Commander and Director of WES during the investigation. Dr. Robert W. Whalin was Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.1745329	radians
inches	2.54	centimeters
feet	0.3048	meters

SEISMIC REFRACTION DATA PROCESSING SOFTWARE

SEISMO VERSION 2.7

PART I: INTRODUCTION

1. The software package "SEISMO" will perform seismic refraction data reduction, interpretation, and presentation. SEISMO will do both forward and inverse modeling of refraction data, calculation of results, display of results, and final report figure presentation of results. The basic concepts of seismic refraction surveying and the procedures for forward and inverse modeling of refraction data are presented in Appendixes A and B, respectively.

2. This program is not presented as a state-of-the-art procedure for seismic refraction data reduction and modeling. The program uses an algorithm that has been in use for several years (time intercept method). Although more complicated algorithms, such as the general reciprocal method, exist, these algorithms also require a more sophisticated understanding of seismic theory. In addition, the more complicated algorithms require more data collection. The algorithm used in this program is a means of obtaining and reducing seismic data, which will suffice for most engineering applications.

Manual Layout

3. Part I of this document gives an overview of SEISMO, the basic steps to running the program, hardware and software requirements, and the installation procedure. Part II explains how to start the program, and discusses the main and control menus, including their operation. Parts III - X explain in detail how to use SEISMO to process data and obtain results. These chapters explain the main menus along with all their options, giving a step-by-step description of how each one functions in the program. Appendix A gives the formulas and conventions used in the forward modeling routine. Appendix B gives the formulas for seismic refraction depth calculations, terrain corrections, and shot depth corrections. Appendix C gives examples of field work performed and analyzed with the SEISMO program.

Typographic Convention

4. The following is a list of the typographic convention used throughout this guide.

"press"	Key indicated should be pressed.
<return>	Enter or return key should be pressed.
"type"	Type the information requested and press enter or return.
<Esc>	Press key labeled "Esc" on the keypad.
" ^ "	The control character indicating that the control key (Ctrl) should be pressed and held down while pressing the second indicated key.

PART II: REQUIREMENTS

5. This section of the report gives an overview of SEISMO's features and functions, and describes the hardware and software configuration the system must have for SEISMO to run properly. The last portion of this section explains in general terms how to use the program. The individual menus and features of each menu are described in detail in subsequent parts of this report.

Overview

6. The SEISMO program was written to provide an aid to analyzing and presenting surface seismic refraction test data. The basic philosophy for this program is to provide a user-friendly, yet powerful, tool that would allow reducing data in a field environment with a portable computer (no pencils, paper, or calculator). This is not an expert system, in that it depends on user knowledge and experience to model the data. With SEISMO one can:

- a. Perform both forward and inverse modeling.
- b. Have complete control over the modeling of data:
  - . Keyboard entry of velocities and intercepts.
  - . Full-screen digitization of model from data.
- c. Easily enter field data.
- d. Perform editing of both input data and input models:
  - . Full-screen editing of data.
  - . Full-screen editing of model in both tabular and graphic form.
- e. Store data.
- f. Have multiple choices of output:
  - . Large 5 by 7 plot of data and model
  - . Report-ready plot of data, model, and calculated results.
  - . Print of input model and calculated results.
  - . Storage of finished plot to disk.
- g. Perform arrival-time corrections:
  - . Shot point depth.
  - . Terrain variations.
- h. Receive on-line help for SEISMO operations.
- i. Have easy access to the Disk Operating System (DOS) environment from within program.

Most of the functions have error-trapping capabilities that will alert the user to errors or possible errors.

Basic Steps to Using SEISMO

7. The following is a step-by-step procedure for the input, modeling, and calculation of seismic refraction data. Each item first describes the process in words and then in SEISMO command terminology.

   a. Enter the field data, geophone distance versus arrival time.
      File Build
   b. Display the data on the screen and digitize the model (or alternately enter the model from the keyboard).
      invMod Screen or invMOD Input
   c. Calculate the model.
      invMOD Calculate
   d. Get printed or plotted output of the data and results.
      Results Printer or Plot Plotter
   e. Store the data and model before exiting program.
      File Write

Hardware and Software Requirements

8. The SEISMO program was developed under Microsoft(MS)-DOS using Microsoft Quickbasic version 4.5 and QuickPak Professional. Version 2.7 of the program supports differing hardware setups using the installation routine to customize the program for the user's particular setup (see paragraph 71).

General requirements : IBM Personal Computer or "compatible."

256K Random access memory available.

MS-DOS 2.0 or higher.

Plotter that interprets Hewlett Packard (HP) graphic language (GL) commands.

Printer

Color graphics adapter (CGA), extended graphics adapter(EGA), or very high resolution graphics adapter (VGA) graphics card.

SEISMO will run on a computer that has a math co-processor installed as well as one that does not. The math co-processor is not necessary, since the program was compiled as if a co-processor did not exist. This makes SEISMO more flexible for varying computers and configurations. It does not, however, noticeably slow the program execution by not utilizing a math co-processor, since the program is not computationally intensive.

Plotters and Printers Supported

9. The plotter must be connected to either serial port 1 or 2 (com1 or com2). This requires the computer to have an RS-232-type serial port to transmit the data to the plotter. All plotting commands coming from the program are in HP-GL language. This requires the plotter to be either an HP plotter or one that will interpret such commands. By using the option to plot to a file (paragraph 33) there is the availability to produce plots on the HP LaserJet or a similar device. The program will support any printer connected to a parallel (LPT) port.

Software Requirements

10. The SEISMO program consists of one program disk. The program is not write-protected and can be copied. The program can be run from either a floppy or hard disk, but the files that end in the extension "pic" must be present in the directory where the program is running. The files contained on the SEISMO disk are listed below.

Name of File	Purpose of File
SEISMO.exe	Invokes the SEISMO program
Scrn1.pic	Control menu for data input
Scrn2.pic	Control menu for model input
Scrn3.pic	Control menu to input/edit data

Name of File	Purpose of File
Scrn4.pic	Control menu for plotter input
Scrn5.pic	Control menu for installation
Scrn6.pic	Control menu for plotter input
Help1.pic	Display of help screen
Help2.pic	Continuation of help screen

PART III: PROGRAM OVERVIEW

Starting the Program

11. To begin the program, the user types "SEISMO" and presses return. The program will then display a screen that has the program information header. This screen will remain for 2 seconds before the main menu appears. The information header contains the name of the program and the version number. It also contains the author's names as well as phone numbers where they may be reached in case of difficulties. Before the main menu appears, the program queries the printer to determine if it is on-line. If the printer is not ready to receive output, the program will display a screen as shown in Figure 1. The length of time the screen remains will depend on the type of hardware used. The user chooses the appropriate response and continues with the program. The program then establishes the system configuration and several defaults. The plotter port is set to be com1, the printer port to be lpt1, and the units to be feet. These choices can be changed in the installation routine discussed in Part X. The program also queries the monitor and establishes the graphics capabilities (CGA, EGA, VGA, etc.).

PRINTER NOT READY:

TO TRY AGAIN < RETURN >

TO ACCEPT < Esc >

Figure 1. Printer error menu

The Main Menu

12. A display of the main menu is presented in Figure 2. The top portion of the menu presents the programming information header. It gives the program name, a brief description of the program, and version level. At the center of the screen is a line entitled 'Menus,' followed by the words FILE, PLOT, EDIT, invMOD, forMOD, RESULTS, and SYSTEM. Each of these words represents a different group of options available in the program. Under the word FILE a selection icon consisting of four red smiling faces should appear.

```
                    ****** SEISMO ******
   Seismic Refraction Data Analysis and Presentaion Software
                  ******** v2.7 Apr 90 ********
-----------------------------------------------------------------
                To Select Menus Use: arrow keys

Menus:  | FILE | PLOT | EDIT | invMOD | forMOD | RESULTS | SYSTEM |
          ☺☺☺☺
Options:

     Build (new)                      <<< select option
     Read (existing)                  enter Highlighted letter
     Write (to disk)
     Print (data)
```

Figure 2. The main menu

This selection icon (cursor) indicates the position on the Menus line. The cursor can be moved to the next heading by pressing the <right/left> arrow keys or the <enter> key. The cursor wraps around when the end of the Menus line is reached. In other words, if the cursor is under FILE, to move to SYSTEM the user presses the left arrow once, and the cursor will "jump" to SYSTEM. As the cursor is moved through the Menus choices, the options under each are updated. The choices are easy to locate, they are on the left of the screen under the word Options. To perform the option, the user presses the letter corresponding to the highlighted letter in the option. This is stated to the right of the options list. When an option is selected, the program will branch to the control menu that corresponds to that particular option. A description of the various options available under each menu is presented in detail in the corresponding chapters.

Control Menus

13. After selecting an option from one of the menus discussed in paragraph 11, the program branches to the control menu for that option. The control menus for each option all follow the same rules. Movement within the control menus and exit from the menus are consistent from one option to the other. The control menus will have questions that require input by the user from the keyboard. To the right of each question will appear a highlighted box, where the answer to the question is entered. This box will be referred to as a field. Two types of movement are allowed in the control menu, movement within a field and movement between fields. An example of a typical control menu is given in Figure 3. The following keys are active in the control menus.

Movement between fields:

Key	Action
Down arrow	Moves the cursor to the next field (this movement may be down in some cases or to the right in others).
Up arrow	Moves the cursor to the next field (this movement may be up in some cases or to the left in others).
PgDn	Moves the cursor to the last field on the screen.
PgUp	Moves the cursor to the first field on the screen.
Enter	Moves the cursor down or right to the next field in the sequence.
Esc	Aborts entry and exits the screen

Movement within a field:

Key	Action
Any alpha/ numeric key	Enters any character permitted by the field, a number or letter.
Left arrow	Movement to the left.
Right arrow	Movement to the right.
Home	Cursor moves to the far left of the box.
End	Cursor moves to the far right of the box.
Ins	Switches between insert and typeover mode. On most monitors the cursor appears as a block in the insert mode and an underscore in the typeover mode.
Del	Deletes the character under the cursor.
Backspace	Movement to the left.
Space bar	Movement to the right.
Enter	Completes a field entry and moves the cursor to the next field.

After entering a field, a message to assist in answering the question may be printed at the bottom of the screen. This does not occur for every field, but it does for most of the fields. Some of the fields already have answers in them. These answers are default values that the program will use unless they are changed. These answers can be changed by using the editing keys described above.

PART IV: FILE MENU

14. This is the first menu in the Menus line. It is designed to be the default menu when the program is first started. As such, the red selection bar should appear beneath the word FILE. A list of options (begin with red first letter) available for this menu should also appear. The options available are:

Build (new)
Read (existing)
Write (to disk)
Print (data)

The screen should appear as that in Figure 2. If it does not, the user should check the selection bar. If it is not under the word FILE, the <right/left> arrow keys are used to position the cursor there. The user selects the option to perform by typing the red letter corresponding to that option.

Build (New)

15. This option is invoked by typing the letter <b>. The control menu for this option should appear and resemble that of Figure 3. As the name implies, this option is used to build a new file. This would consist of entering the time-distance field data for the refraction line. Before the actual data are entered, however, there are some questions to answer.

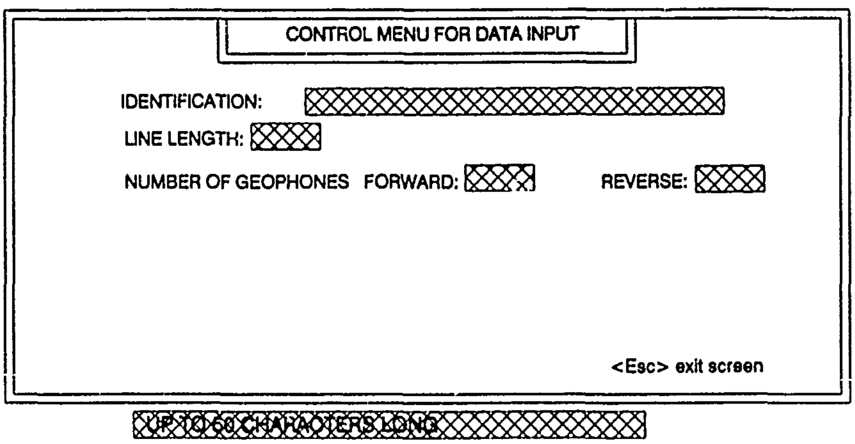


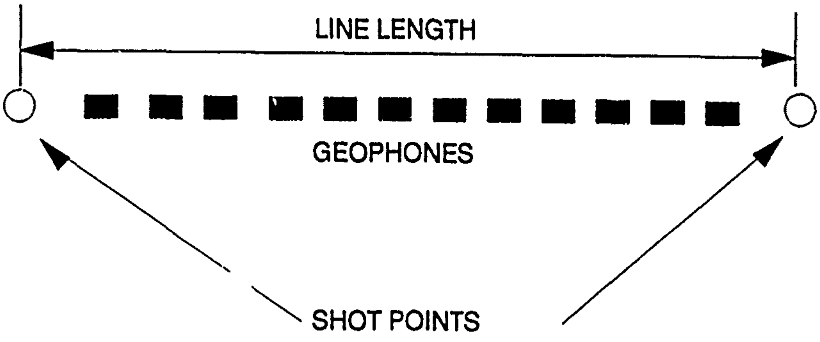
Figure 3. Control menu for data input

Identification

16. This information is used to help identify the time-distance data that will be entered. The identification will be written to disk along with the data. This is to assist in recognizing the data at some future date. All keys are active in this field.

Line length

17. The line length is defined to be the distance from shot point to shot point. If only a forward shot is done, then the line length is the distance from the shot to the last geophone. An example of the correct line length, given a spread with 12 geophones spaced 10 ft* apart and a source at both the forward and reverse end, spaced 10 ft from the nearest geophone, is presented in Figure 4.



line length = 10 ft + (12-1)*10 + 10 ft = 130 ft

Figure 4. Line length calculation

Number of geophones

18. This is the number of geophones in the spread. The program can handle up to 48 geophones. There are two inputs to complete this question. The user enters the number of forward geophones (48 maximum), and the number of reverse geophones (48 maximum). Normally the number of forward geophones will equal the number of reverse geophones for a particular spread since they are usually coincidental. However, this need not be the case. To exit the screen and begin data input the user presses the escape key as instructed at the bottom of the screen.

---

* A table of factors for converting non-SI units of measurement to SI (metric) units is found on page 4.

Data input screen

19. This is the screen where the actual field data are entered (time-distance). The screen should appear as that in Figure 5. The screen contains several fields, with headings of DISTANCE and TIME. The cursor will be in the first field under the heading DISTANCE. The user enters the necessary distance and time data, and presses <enter> or the <up/down> arrow keys after each entry. The cursor will then move to the next field. When a value is entered in the distance field, the program uses that value to predict the next distance value. The predicted distance will automatically be entered by the program in the upcoming distance field. The user either accepts the predicted distance value by pressing enter or the down arrow, or changes the value. The program will then use the new value to predict the next distance value. To change a value, the editing keys (Ins, Del, etc.) that are active inside a field are used. The status message in the lower left corner of the screen is updated to indicate which data point is being entered (or should be entered). It also reports if the forward or reverse data set is being entered. In the same location is a box indicating which screen is active and how many screens are necessary to complete data input. In the lower right corner of the screen is information about exiting the routine. To exit the input screen, the user presses <Esc>. This will store the data in memory and return to the main menu. There are two other options to help in manipulating the screen if multiple screens are needed for data input. If more than 24 points are being entered, then multiple screens are used. The user pages through the screens by using the ^PgUp or ^PgDn keys.

Line length errors

20. At the conclusion of data input and upon exiting the routine, the program will perform a check of the line length. The line length is calculated using the number of geophones and the distance between those geophones. If the calculated distance in this check does not correspond to that entered in the build file routine, then the program will print an error message and correct the line length. The program then uses the corrected line length for all subsequent operations.

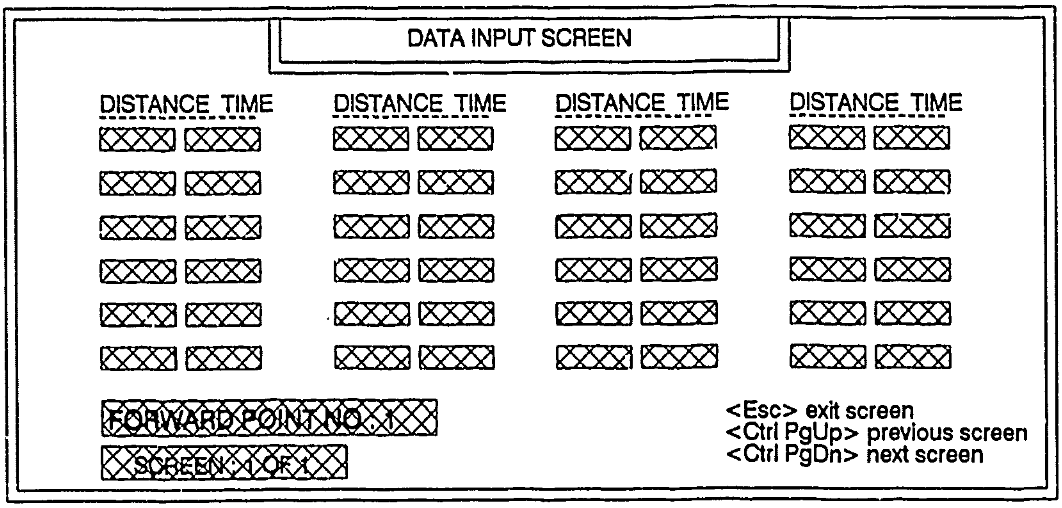


Figure 5. Data input screen

Read (Existing)

21. This routine is used to read an existing data file from disk (hard or floppy). Upon entering this routine, a question appears that asks the name of the file to access. There will also be a comment about the extension. All data files written from SEISMO have a ".ref" extension added to them. This will assist in recognizing data files produced from within SEISMO. The user types in the name of the file (without extension) and presses <enter>. The program will search for the file and read the data. If just the file name is entered, the program searches in the current directory only. To retrieve data from another directory or another drive, the user enters the complete path with the file name. If an incorrect name is entered the program will print a screen as shown in Figure 6.

```
FILE.REF DOES NOT EXIST
        < RETURN > TO TRY AGAIN
        < Esc > TO ABORT
        < D > TO DIR ALL .REF FILES
```

Figure 6. File listing routine

The program prints that there are no ".ref" files at the location specified and presents three choices. The user presses <return>, at which point the program will ask for the file name again. Choice two is to press <Esc> and abort the whole process, which then returns control to the main menu. The third choice is to press < D > to get a listing of all ".ref" files in the directory specified. If this option is selected, the SEISMO directory screen (Figure 7) will appear. Enter the directory to search for any ".ref" files. By pressing <return> a listing of the current directory will appear. To search another directory or drive, the user types in the full path name to that directory including the ".ref" extension and then follows the directions on the screen to input the file.

5 file(s) found

FILE1.REF FILE2.REF FILE3.RER FILE4.REF FILE5.REF

Filename: file1.ref

Use cursor keys to select file then press <ENTER>

Figure 7. List of matching files display

<u>Write (To Disk)</u>

22. This routine writes data to the specified drive\directory\file name. Here again, the user does not enter an extension; SEISMO will add a ".ref" extension. If no drive\directory is specified, the file is written to the current directory. The file name is limited to eight characters, not counting the extension. All MS-DOS rules must be followed. The file contains the following information.

```
title,#forward geophones,#reverse geophones,line length,#layers
distance(1),time(1)
distance(2),time(2)
    ...
    ...
distance(last),time(last)
forward velocity(1),forward intercept(1)
    ...
    ...
forward velocity(last),forward intercept(last)
reverse velocity(1),reverse intercept(1)
    ...
    ...
reverse velocity(last),reverse intercept(last)
```

The velocity and intercept information pertains to the inverse model which will be discussed in Part VI. If the file already exists, a message will appear to that effect, and the user follows the information on the screen to continue.

Print (Data)

23. This routine will send a print of the selected data currently in memory to the installed printer. There are three types of data printouts; the uncorrected time-distance data, the terrain-corrected data, and the forward model calculated data. The printouts will resemble those in Figures 8, 9, and 10, respectively. If there are no data in memory, the program will print a message to that effect and return to the main menu.

SEISMIC DATA SUMMARY

DATA FILE NAME : WSB4R7.REF
DATA IDENTIFICATION : wsb4r7
THERE ARE : 24 FORWARD POINTS 24 REVERSE POINTS
LINE LENGTH : 50 ft

*** FORWARD POINTS ***		*** REVERSE POINTS ***	
Distance ft	Time msec	Distance ft	Time msec
2.0	4.0	2.0	4.0
4.0	7.0	4.0	7.0
6.0	8.0	6.0	8.5
8.0	8.5	8.0	9.0
10.0	9.0	10.0	10.0
12.0	11.0	12.0	11.0
14.0	11.5	14.0	12.0
16.0	15.0	16.0	12.5
18.0	14.0	18.0	14.0
20.0	14.3	20.0	15.5
22.0	15.5	22.0	16.0
24.0	16.5	24.0	16.5
26.0	17.0	26.0	17.0
28.0	18.0	28.0	17.5
30.0	18.5	30.0	19.0
32.0	20.5	32.0	20.0
34.0	21.0	34.0	21.0
36.0	22.0	36.0	22.0
38.0	24.0	38.0	23.5
40.0	25.0	40.0	25.0
42.0	27.5	42.0	27.0
44.0	28.0	44.0	28.0
46.0	29.0	46.0	30.0
48.0	30.0	48.0	31.0

END OF DATA

MODEL SAVED WITH DATA

*** FORWARD MODEL ***		*** REVERSE MODEL ***	
Velocity ft/sec	Intercept msec	Velocity ft/sec	Intercept msec
542	0.0	512	0.0
1836	3.7	1780	4.0

Figure 8. Printout of uncorrected time-distance data

SEISMIC DATA SUMMARY

DATA FILE NAME : WSB4R7.REF
DATA IDENTIFICATION : wsb4r7
THERE ARE : 24 FORWARD POINTS 24 REVERSE POINTS
LINE LENGTH : 50 ft

*** FORWARD POINTS ***					*** REVERSE POINTS ***				
Dist ft	UTime msec	CTime msec	Cor ft	CVel ft/sec	Dist ft	UTime msec	CTime msec	Cor ft	CVel ft/sec
2.0	4.0	3.9	0.5	527.0	2.0	4.0	4.0	0.0	527.0
4.0	7.0	7.9	0.5	527.0	4.0	7.0	7.0	0.0	527.0
6.0	8.0	8.9	0.5	527.0	6.0	8.5	8.5	0.0	527.0
8.0	8.5	9.4	0.5	527.0	8.0	9.0	9.9	0.5	527.0
10.0	9.0	9.9	0.5	527.0	10.0	10.0	10.9	0.5	527.0
12.0	11.0	12.8	1.0	527.0	12.0	11.0	11.9	0.5	527.0
14.0	11.5	13.3	1.0	527.0	14.0	12.0	12.9	0.5	527.0
16.0	15.0	16.8	1.0	527.0	16.0	12.5	13.4	0.5	527.0
18.0	14.0	15.8	1.0	527.0	18.0	14.0	14.9	0.5	527.0
20.0	14.3	16.1	1.0	527.0	20.0	15.5	16.4	0.5	527.0
22.0	15.5	17.3	1.0	527.0	22.0	16.0	16.9	0.5	527.0
24.0	16.5	18.3	1.0	527.0	24.0	16.5	17.4	0.5	527.0
26.0	17.0	17.9	0.5	527.0	26.0	17.0	18.8	1.0	527.0
28.0	18.0	18.9	0.5	527.0	28.0	17.5	19.3	1.0	527.0
30.0	18.5	19.4	0.5	527.0	30.0	19.0	20.8	1.0	527.0
32.0	20.5	21.4	0.5	527.0	32.0	20.0	21.8	1.0	527.0
34.0	21.0	21.9	0.5	527.0	34.0	21.0	22.8	1.0	527.0
36.0	22.0	22.9	0.5	527.0	36.0	22.0	23.8	1.0	527.0
38.0	24.0	24.9	0.5	527.0	38.0	23.5	25.3	1.0	527.0
40.0	25.0	25.9	0.5	527.0	40.0	25.0	25.9	0.5	527.0
42.0	27.5	28.4	0.5	527.0	42.0	27.0	27.9	0.5	527.0
44.0	28.0	28.0	0.0	527.0	44.0	28.0	28.9	0.5	527.0
46.0	29.0	29.0	0.0	527.0	46.0	30.0	30.9	0.5	527.0
48.0	30.0	30.0	0.0	527.0	48.0	31.0	31.9	0.5	527.0

END OF DATA

MODEL SAVED WITH DATA

*** FORWARD MODEL ***		*** REVERSE MODEL ***	
Velocity ft/sec	Intercept msec	Velocity ft/sec	Intercept msec
512	0.0	512	0.0
1836	3.7	1780	4.0

Figure 9. Printout of terrain and shot point corrected data

SEISMIC DATA SUMMARY

DATA FILE NAME : WSB4R7.REF
DATA IDENTIFICATION : wsb4r7
THERE ARE : 24 FORWARD POINTS 24 REVERSE POINTS
LINE LENGTH : 240 ft

*** FORWARD POINTS ***		*** REVERSE POINTS ***	
Distance ft	Time msec	Distance ft	Time msec
10.0	11.1	10.0	11.1
20.0	18.4	20.0	18.4
30.0	22.4	30.0	22.4
40.0	26.4	40.0	26.4
50.0	29.0	50.0	29.0
60.0	30.3	60.0	30.3
70.0	31.7	70.0	31.7
80.0	33.0	80.0	33.0
90.0	34.3	90.0	34.3
100.0	35.7	100.0	35.7
110.0	37.0	110.0	37.0
120.0	38.3	120.0	38.3
130.0	39.7	130.0	39.7
140.0	41.0	140.0	41.0
150.0	42.3	150.0	42.3
160.0	43.7	160.0	43.7
170.0	45.0	170.0	45.0
180.0	46.0	180.0	46.0
190.0	47.0	190.0	47.0
200.0	48.0	200.0	48.0
210.0	49.0	210.0	49.0
220.0	50.0	220.0	50.0
230.0	51.0	230.0	51.0
240.0	52.0	240.0	52.0

END OF DATA

MODEL SAVED WITH DATA

*** FORWARD MODEL ***		*** REVERSE MODEL ***	
Velocity ft/sec	Intercept msec	Velocity ft/sec	Intercept msec
900	0.0	900	0.0
2500	10.4	2500	10.4
7500	22.4	7500	22.4
10000	28.0	10000	28.0

Figure 10. Printout of forward model calculated data

PART V: PLOT MENU

24. The second menu in the menus line contains the plotting options. When the cursor is beneath the word PLOT, the screen should appear as that in Figure 11. There are four options available from the PLOT menu. The options are Screen, Plotter, File, and Overlay plot. Each option is discussed in detail below. The user selects the option by typing the highlighted letter corresponding to the option.

```
****** SEISMO ******
Seismic Refraction Data Analysis and Presentaion Software
******** v2.7 Apr 90 ********
---------------------------------------------------------------

To Select Menus Use: arrow keys

Menus: | FILE | PLOT | EDIT | invMOD | forMOD | RESULTS | SYSTEM |
Options:

      Screen                             <<< select option
      Plotter                            enter Highlighted letter
      File
      Overlay plot
```

Figure 11. Main menu (plot)

Screen

25. This option is used to plot the time-distance data to the screen. It is also used to display the model, if one exists, or enter the model, if one does not exist. The screen should appear as that presented in Figure 12. If a CGA screen is present, the presentation will be in black and white. If an EGA or VGA screen is present, the presentation will be in color. The primary function of this routine is to be able to see data before making a hard copy. However, it is possible to input a model with this routine as explained in detail in paragraph 45.

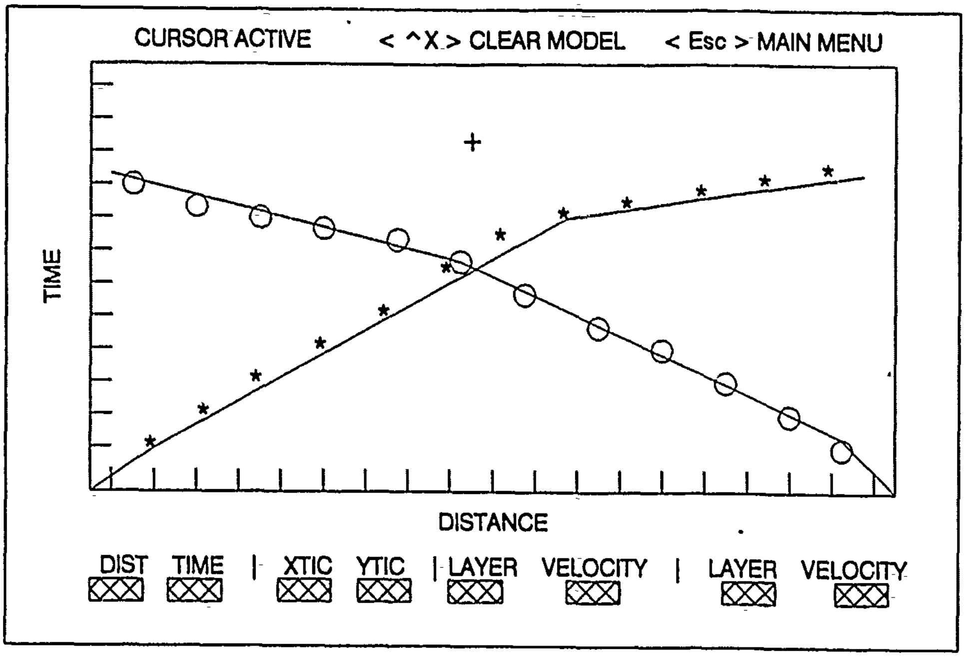


Figure 12. Screen model digitization

Plotter

26. This routine is used to make a hard copy plot of the data. This would include the time-distance values as well as the model, if one exists. This routine does not present any calculated results (depths to interfaces and true velocities). The routine produces a 5- by 7-in. plot of the input data. This routine was added to give the user a working copy of the data and model before finalizing the results. Upon entering this option, the program branches to the plotter control menu which is described in paragraph 28. An example plot is presented in Figure 13. At the top of the plot is a banner that contains information relative to the plot. The first line contains the title entered from the plotter control menu and described in the following sections. The second line contains the name of the file where the information is contained. This is very useful as a means of keeping track of where data are located.

Plotter control menu

27. This menu is used to set parameters required by the plotter. The plotter control menu should resemble that in Figure 14. There are eight questions on the plotter control menu that require input from the user. These

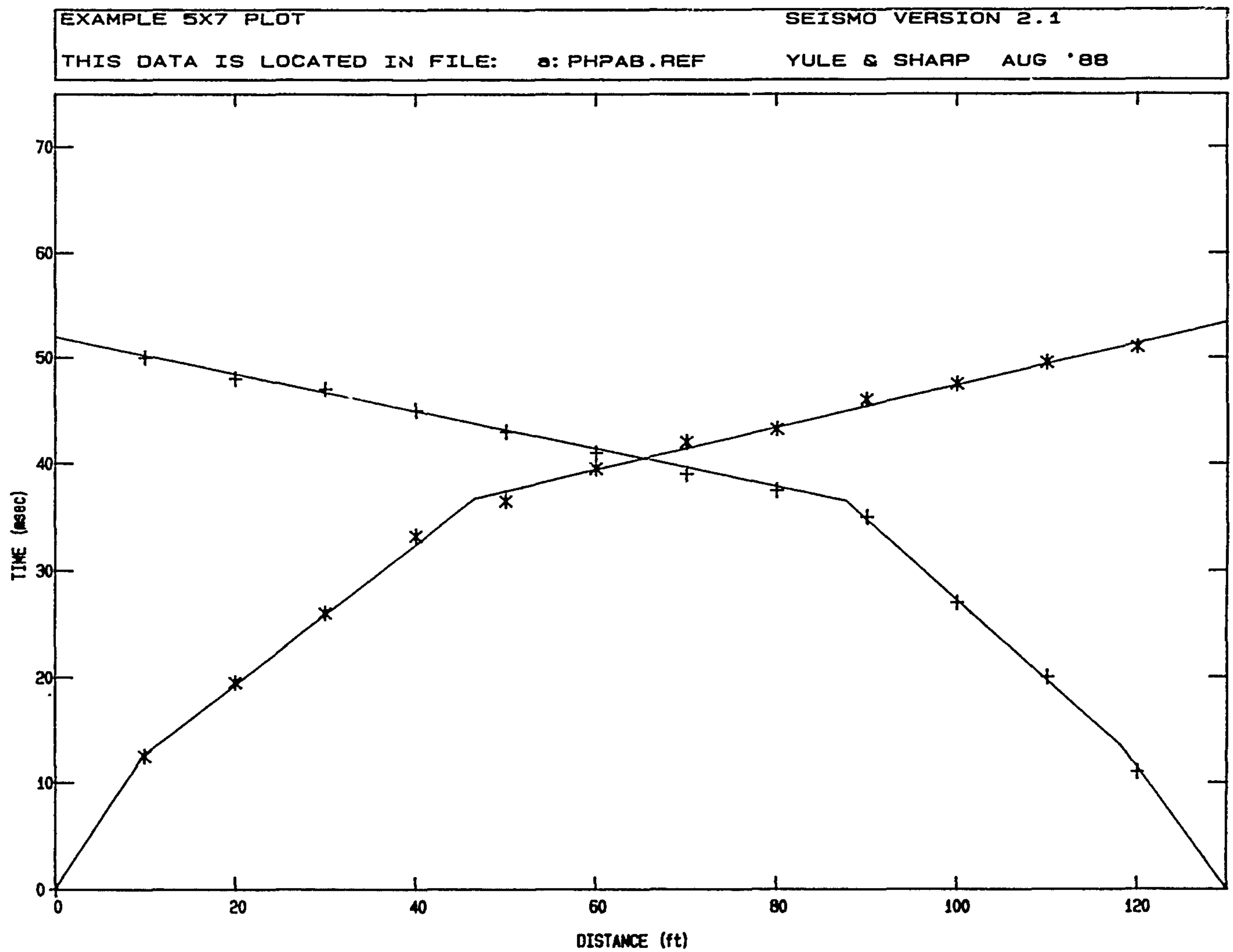


Figure 13. Example 5- by 7-in. output plot

questions involve scaling and labeling for the plot. Each item is described in detail in the sections following.

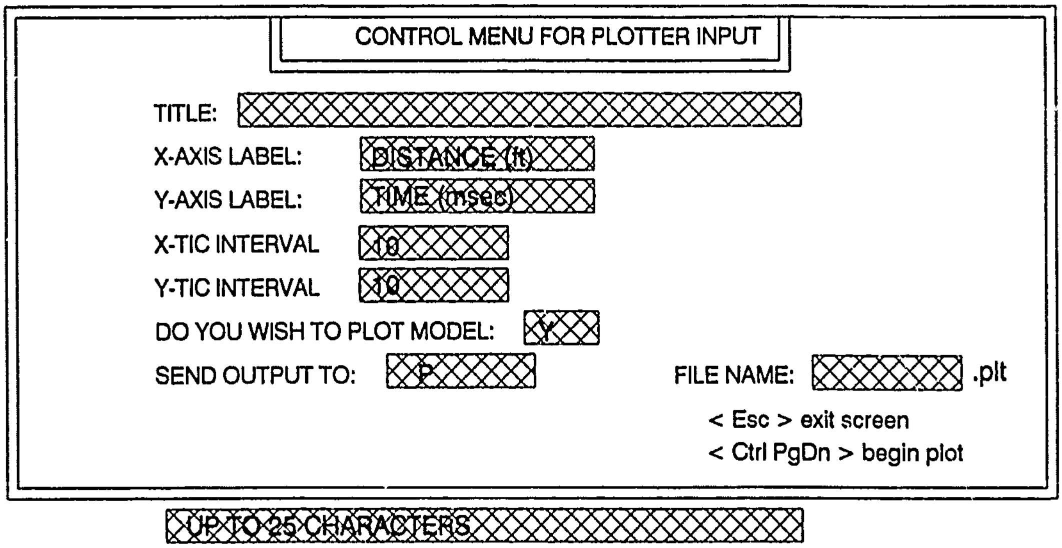


Figure 14. Control menu for plotter input

Title

28. This is the title that will actually be displayed on the plot. There are no restrictions as to what may be entered in the title field. All keys are active for this particular field. However, there are limitations on how long the title can be. Typing outside the field, denoted by the highlighted box beside the word TITLE, is not allowed. There are a total of 50 character spaces in the title field. If a title on the plot is not desired, the user leaves the field blank.

X-axis and y-axis labels

29. These are the labels for the axis on the plot. Both these fields should have default values in them. The x-axis is normally labeled "Distance, ft" and the y-axis is labeled "Time, msec." These labels can of course be changed, and if metric units are being used, will have to be changed. Here again, the field will accept any character, and input is limited only by the size of the field.

X-tic and y-tic intervals

30. These variables control the number of tics on each respective axis. Default values for these fields are given in feet. Default values are not

intended to be used for all cases. For example, if there is a line length of 1,200 ft and selected default x-tic intervals of 10 ft are used, then 120 tics will appear across the x-axis. On the plot this will look like a solid dark line after the tic labels are added. In this case, the user should select a larger tic interval for the axis.

Model option

31. There is a choice in this menu to either plot the model or not plot the model. This is convenient in that it allows the user the option of sketching in his own model. This may be necessary in cases where the model cannot be reasonably discerned from the screen digitizing routine. The answer to this question is a "yes" or "no" and is entered by typing <y> or <n>. The default selection is "yes."

Plot destination

32. The next two questions in the plotter control menu concern the destination of the plot. The plot can be sent directly to the plotter, or it can be sent to a file for later use. This option is convenient if a plotter is not readily accessible. Remembering that SEISMO was developed as a useful tool for field data collection and interpretation, there will be times when a plotter is not available. Plots can still be made, however, and saved to a file to be plotted at some later date. The answer to the question "SEND OUTPUT TO" is <p> for plotter or <f> for file. The field has a default answer of "p." If <f> is selected, then the user inputs a file name or uses the default file name. Normally there will be a default name in the "FILE NAME" field. This name will coincide with the name entered for data storage from the "Build" routine. The name can be changed, but all plot files have a ".plt" extension. This extension will be added by the program and need not be typed in. If the user does not want to plot to a file, then this option can be left either blank or at the default value.

Begin the plot

33. To complete the plotter control menu input and continue with the plot, the user presses < ^ PgDn>. The plotter will be activated and a plot should be made. This requires the plotter to be connected to the appropriate serial port and to be on-line. If the plotter is not ready, an error will be generated and an error message displayed. To exit the screen and abort the plotting process, the user presses <Esc>.

File (To Plotter)

34. This option will read a plot file from the specified drive\directory\file name and send the data to a plotter. The same routine used to read a data file and discussed in paragraph 22 is utilized here. The functions and operations are exactly as described in that section, the only difference being that the user is working with ".plt" files here instead of ".ref" files. The user should be sure that the plotter is connected and on-line before performing this option. This routine handles both the 5-by 7-in. working plots discussed in paragraph 27 as well as the final plate plots discussed in paragraph 66.

Overlay Plot

35. This routine will allow the plotting of more than one set of data points on the same plot. This refers to hard copy plots only, and not to plots on the screen. If more than one set of data is to be plotted to the same plot, this is the routine to follow. The user reads in the original data set and makes a plot as described in paragraph 27 or paragraph 66. Leaving the plot on the plotter, the user reads in a second data file. The user moves to the PLOT menu and selects this option (overlay plot). A message to the effect that the overlay plot is working will be displayed on the screen. The data will then be plotted on the plot already in the plotter. This can be done as many times as the user wishes for as many data sets as desired on one plot. However, all data sets are plotted on the scale (distance versus time) dictated by the original plot. This routine applies to data only, not data and models, only one model per plot.

PART VI: EDIT MENU

36. The edit menu is used to edit both data and inverse models. Upon selecting this menu (EDIT) the screen should appear as does Figure 15. These are not input options, but are used to edit existing data or models.

```
****** SEISMO ******
Seismic Refraction Data Analysis and Presentaion Software
******** v2.7 Apr 90 ********
----------------------------------------------------------------------

To Select Menus Use: arrow keys
Menus: | FILE | PLOT | EDIT | InvMOD | forMOD | RESULTS | SYSTEM |
                        ☺☺☺☺
Options:

        Data                          <<< select option
        Inverse model                 enter Highlighted letter
```

Figure 15. Main menu (edit)

Data

37. These are the time and distance data that were entered from the FILE menu (build or read) and described in the sections above. An example of the menu to edit data is shown in Figure 5. This is the same menu used for the data input routine, and follows the guides expressed in paragraph 20.

Inverse Model

38. The second edit option involves the inverse model. For a complete description of the inverse model and the means of input, see Part VI. The menu used to edit the model is the same as that described in paragraph 41 for inputting the model from the keyboard. The menu should appear as that of Figure 16. The control menu for model editing (and input) is described in detail in Part VI which can be consulted for the function of each field and

the appropriate response. If a model has been entered to edit, then that model should be displayed in the control menu. The number of layers, velocities, and time intercepts will be in their appropriate fields. To edit the model, the keys as described in paragraph 12 can be used to move to the field and perform the correction. If adding or deleting a layer, the user should be sure that the number in the NUMBER OF LAYERS field reflects the change.

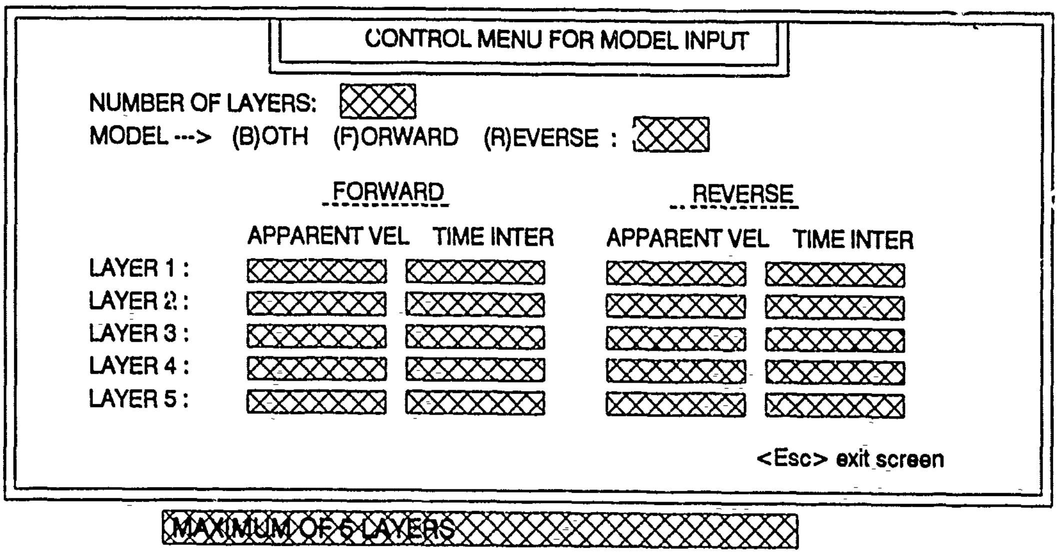


Figure 16. Control menu for model input

PART VII: invMOD MENU

39. This menu concerns the various options related to the inverse model as well as the terrain and shot point corrections. The menu should appear as that in Figure 17. The program will do two types of modeling, inverse and forward. Inverse modeling is the entry of apparent velocities and intercepts with subsequent calculation of the model (depths to interfaces and true velocities). Forward modeling is the entry of depths and true velocities with subsequent calculation of apparent velocities and intercepts. The normal process of data reduction would be the input of the inverse model. This chapter deals with the input and manipulation of the inverse model.

```
                    ****** SEISMO ******
     Seismic Refraction Data Analysis and Presentaion Software
                ******** v2.7 Apr 90 ********
-----------------------------------------------------------------

                To Select Menu: Use arrow keys
 Menus: | FILE | PLOT | EDIT | invMOD | forMOD | RESULTS | SYSTEM |
 Options:

        Input    (from keyboard)          <<< select option
        Screen   (digitize)               enter Highlighted letter
        Calculate
        Terrain/shot corrections
```

Figure 17. Main menu (invMOD)

Input

40. This option concerns inputting the inverse model from the keyboard. Upon selection of this option, the control menu for model input as presented in Figure 16 will appear. This menu has two questions followed by enough fields to input up to five layers forward and reverse.

Number of layers

41. This is the number of layers that will be used to model the data. The program will handle up to five layers. For most cases there will be an equal number of forward and reverse layers. If, however, there is a case where this is not true, the modeling will have to be done in two steps. This would involve modeling the layers for the forward traverse and calculating them, then modeling the layers for the reverse traverse and calculating them. This is accomplished by using the "MODEL" option from the model input screen. Such a case could occur, for instance, if there is a layer that pinches out (consult Appendix A for a discussion of this and other such occurrences).

Model

42. SEISMO can model three separate cases: both a forward and reverse traverse, forward traverse only, and reverse traverse only. There are times when only a forward shot of a seismic line is performed. If this is the case, that can be modeled in SEISMO. It is not recommended that this be a common field practice, and the user should always try to conduct both a forward and reverse shot for the seismic line. By doing a forward shot only, the program can only interpret the interfaces as being horizontal with no indication of possible dipping layers. When entering a forward traverse model only, the program will make the reverse traverse model equal to the forward model input. It is this feature that will allow the input model to not have equal forward and reverse layers, by splitting the model into two parts. The interpretation will then have to be combined, understanding, of course, that it is based on assumed horizontal layers. The default answer for this field is "B," indicating that both a forward and reverse traverse will be modeled.

Velocities and intercepts

43. The velocities that are entered are the apparent velocities, meaning that they are those determined from the field data. The velocities must increase with depth, to prevent any errors. This means that layer 1 velocity is less than layer 2 velocity, layer 2 velocity is less than layer 3 velocity, and so on. The velocities are entered in feet/second or meters/second. The time intercepts are the projections of the velocities (straight line segments) back to the time axis. For the first layer this value will always be a zero. The time intercepts are always entered in milliseconds.

Screen

44. This routine is used to input the model from the screen by digitizing breakpoints. This screen is shown in Figure 9. The cursor for this screen is a "+" sign and should be located in the center of the screen. To determine where the breakpoints are, the user draws straight line segments through the data points. The breakpoints to be digitized are located at the points where the line segments intersect (change in slope). This concept is presented in Figure 18. The points are digitized by moving the cursor to the point, and pressing the appropriate key. The keys active for this screen and the function they perform are described below. The movement of the cursor is controlled in steps determined by the number keys. To change the step size, the user presses a number from one to nine.

KEY	FUNCTION
Right arrow	Moves the cursor to the right.
Left arrow	Moves the cursor to the left.
Up arrow	Moves the cursor up.
Down arrow	Moves the cursor down.
Enter	Returns the cursor to the middle of the screen.
F1-F5	These function keys are for entering the forward breakpoints, this allows entry of five layers.
F6-F10	These function keys are for entering the reverse breakpoints, this allows entry of five layers.
Esc	The escape key will exit the routine at any time.
^x	This will clear the model but not the data.

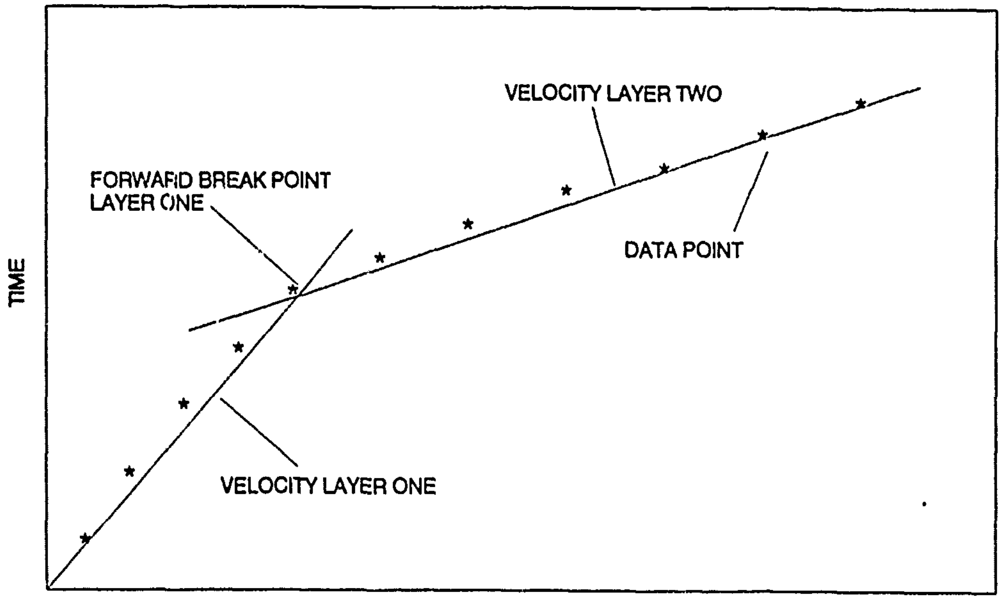


Figure 18. Breakpoint concept

As mentioned above, the escape key is used to exit the routine. It is possible to exit the routine at any time, but the user should be aware that the model on the screen at the point of exit will be saved. After completion of model digitization, the user presses <Esc> to return to the main menu. Warning! If the user presses ^x to clear the model digitized on screen, this will also clear the model read from disk. For example, suppose a file was read from disk, then the data and model were displayed on screen with the "screen" routine above. The forward layer is modified slightly, but not desired to be saved. By pressing ^x the entire model is erased. To recall the model, the user reads the file from disk again.

<u>Information panel</u>

45. At the bottom of the screen are displays that provide useful information to aid the user in this screen. The location of the cursor is displayed at all times under the headings "dist" and "time." This is the x,y position of the cursor relative to the scale used to make the plot. The tic marks on the plot are not labeled, but the tic mark spacings are given under the headings xtic, ytic. More times than not, these will be some unusual number such as xtic = 31.3. The user should not be concerned about odd

scales, as the location of the cursor can always be found by checking the cursor location displays. The displays that show the digitized model input layer velocities are located on the right side of the information panel. There should be four headings; layer, velocity, layer, and velocity. When a breakpoint is digitized, two velocities are being changed: the one behind the breakpoint and the one in front of the breakpoint. The display updates those velocities and the corresponding layer, which is especially useful when editing the model.

Onscreen editing of the model

46. After entering a model, whether by keyboard or screen digitization, SEISMO is extremely useful in editing that model. The user has complete control of where the line segments, representing velocities, should be located. To edit a model, the user moves the cursor to where the new breakpoint (between line segments) should be and presses the appropriate function key. Again, forward breakpoints are controlled by function keys 1-5, and reverse breakpoints by function keys 6-10. As the model is edited, two things will be apparent. First, the display at the lower right of the screen will print the new velocities for the appropriate layer. Secondly, the old line segments will "disappear" and the new line segments will be drawn in. The program does not restrict where a breakpoint may be entered.

Calculate

47. This option is used, in the case of the inverse model, to calculate the true velocities and depths to interfaces from the input model. If there is no model in memory, the program will print out a message to that effect and the calculation will not take place. If there is a model present, the program will print out a message that it is calculating. When the calculation is complete, control is returned to the main menu. The calculation is performed using the time-intercept method described in Appendix A. The calculation routine has an error checking function that alerts the user of possible problems. Theoretically, the forward and reverse total travel time (reciprocal time) for each layer should be the same. The program computes this and alerts the user to any discrepancies. For each layer, the travel time forward is compared with the travel time reverse. If the difference between the two is greater than 10 percent, the program will print a message

to that effect and pause the program. The user presses <enter> to continue the calculation. It is then up to the user to either accept the error or rework the model. It is suggested that the model be reworked, such that the 10-percent travel time error is not surpassed.

Terrain/Shot Corrections

48. This option allows the correction of data for varying shot point depths and varying geophone changes in elevation. In order to utilize this routine, the number of forward geophones must equal the number of reverse geophones, and they must be coincidental. A refraction line should be run in an area as nearly horizontal (constant elevation) as possible. When this is not possible, this routine will correct the measured arrival times to a common datum plane. The datum plane is arbitrary and is chosen by the user. The subsequent corrected arrival times will be the times as if the geophones were located along a horizontal plane extending from the datum point. The program will also correct the arrival times for varying shot depths, effectively correcting the arrival times to a surface source. Prior to the start of the corrections menu, a display will appear that resembles Figure 19. In order to use the routine, the velocity of the first two layers and the first geophone receiving refracted arrivals for the forward and reverse spread must be known. The display (Figure 18) will print the first and second layer velocity presently in memory. These velocities come from the calculations performed on the inverse model. If they do not exist, the program will print zeros as the velocities. The user may accept the velocities printed, input new velocities, or exit the routine. The geophone receiving the first refracted arrival can be obtained by plotting the raw data and observing the breaks in slope. The following paragraphs explain the function of the options in the correction menu. The correction menu will appear as shown in Figure 20.

Scale

49. At the left of the screen is the elevation scale. This scale initially ranges from 5 to -5 in increments of one half. For most normal operations, this scale will be sufficient to cover the elevation changes. To change the scale, the user presses ^s, and answers the question that appears. The entered scale factor is multiplied by the original scale to obtain the new scale. The new scale will then be displayed in place of the old scale.

THIS ROUTINE REQUIRES :

TRUE VELOCITIES OF FIRST TWO LAYERS
GEOPHONE RECIEVING FIRST REFRACTED ARRIVAL

FIRST LAYER TRUE VELOCITY 0

SECOND LAYER TRUE VELOCITY 0

< return > TO ACCEPT VELOCITIES
< Esc > TO ABORT
< I > TO INPUT NEW VELOCITIES

>>>> SELECT

ENTER FIRST LAYER TRUE VELOCITY
ENTER SECOND LAYER TRUE VELOCITY
GEOPHONE RECEIVING FIRST FORWARD REFRACTED ARRIVAL
GEOPHONE RECEIVING FIRST REVERSE REFRACTED ARRIVAL

Figure 19. Pre-correction menu

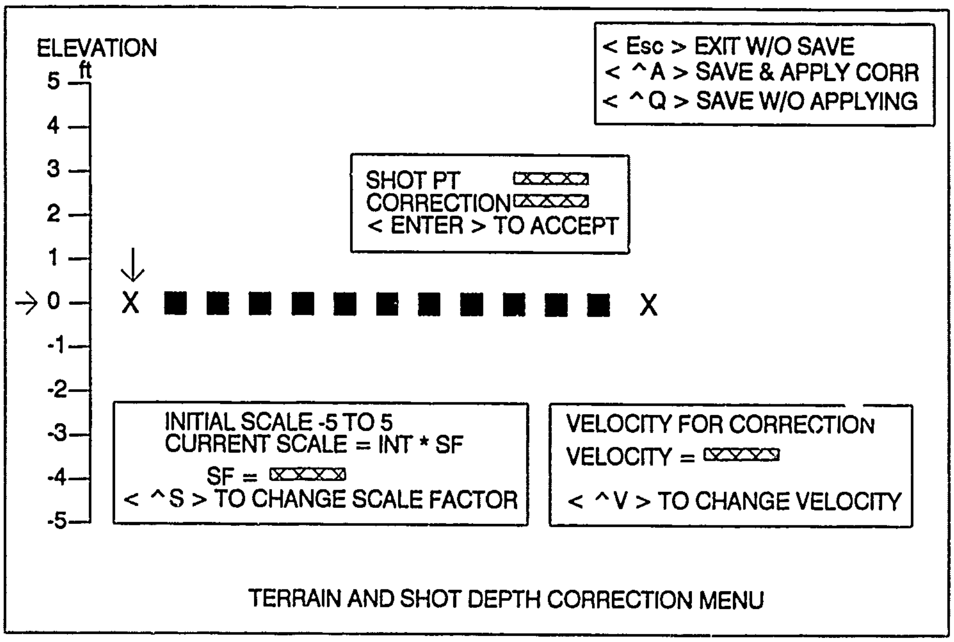


Figure 20. Correction menu

At the bottom left of the screen is printed information to assist in determining the status of the scale. The initial scale is printed since all subsequent scales are referenced to this scale. Then the current scale calculation procedure is displayed, to remind the user of how the present scale was obtained. The current scale factor, which is changed as the scale changes, is also displayed. Example: The scale is as presented initially (5 to -5), the user presses the ^s keys, and enters the new scale factor. The initial scale is multiplied by the scale factor and the new scale is displayed. If a scale factor of "2" was entered, then the new scale will range from 10 to -10 in increments of one. The scale can be changed to any factor desired by utilizing the change scale function. There is no limit as to how small or large the scale will become; however, there is a limit to the degree corrections can be reasonably applied to refraction data. There is a small horizontal arrow pointing to the zero elevation location. This arrow is used to select the elevation that will be entered for the shot point or geophone. Recall that this number is the elevation above or below the datum plane. The arrow is controlled by the up/down arrows on the keypad and will "wrap" at the top or bottom.

Datum plane

50. Located at approximately the center of the screen is the datum plane. There should be two "x's" which represent the shot points for the refraction line. Between the x's are small squares that represent the geophones. There should be as many squares as there are geophones for the spread being corrected. The maximum number of geophones that the program can handle from this menu is 48. Upon entering the screen, there will be a vertical arrow pointing to the first shot point. This arrow marks the shot point or geophone that is being corrected. It is controlled by the <right/left> arrow keys on the keypad and will perform the "wrap" function.

Elevation corrections

51. Located in the center of the screen above the datum plane is information that will be useful to the user as the corrections are applied. The first line informs the user where along the datum plane he is located. If the arrow points to a shot point, the message line reflects that; if it points to a geophone, the message reflects that. The second line gives the correction as entered by the user. To enter the corrections, the user places the vertical arrow over the shot point or geophone to be corrected. The user

places the horizontal arrow at the elevation to be entered and presses <enter>. If proceeding from left to right across the screen, the program will update the vertical arrow. After pressing <enter>, the vertical arrow is moved to the next location on the datum plane. After all the corrections are entered (or during entry), the entries can be reviewed. As the vertical arrow is moved across the datum plane, the information entered for each point is displayed. These can of course be edited by re-entering a new elevation.

Velocities used in corrections

52. In the lower right-hand corner of the screen is located information about the velocities used for the corrections. The velocity can be changed by pressing ^v. Each geophone has its own velocity used to make the correction, and that velocity is displayed for each geophone as the vertical arrow points to it. The velocity is in feet or meters per second. This feature can be used to correct for lateral changes in the top layer velocities.

Exit module

53. At the top right of the screen are located the exiting routines. The first option is to press <Esc>, which is an exit without saving. This option is used to abort the process and return to the main menu. When this option is performed, no information is retained from the correction menu. The second option is to press ^a to save the corrections and apply them to the original data. Be aware that once the corrections are applied, the original data are lost and the corrected data become current in the programs memory. It is recommended that two sets of data be kept, one file containing the original data and a second file containing the corrected data. The third option, pressing ^q, will simply save the corrections in the programs memory but will not apply them to the original data. When exiting the program the corrections are of course lost. All three options will return control to the main menu after performing their indicated function.

Recommended procedure

54. If there are data to be corrected for elevation changes in shot points or terrain, this is the recommended procedure. The user enters the time-distance data and a model (from keyboard or by screen digitization). The user then calculates the results of the model and saves the original uncorrected data. He selects the terrain/shot point corrections option and enters the correction data as described above. He uses the ^a option to exit the routine and apply the corrections. The user replots the data (corrected

now) and edits the model to fit the corrected data. This information is saved under a different file name to keep it separate from the original (uncorrected) data.

PART VIII: forMOD MENU

55. See paragraph 40 for a definition of the forward modeling process. When this menu is selected, the screen should appear as that in Figure 21. This menu will present the options available to the user to perform forward modeling. Forward modeling is useful in that it gives a picture of what can be expected from given field conditions. With this option, the user can have a tool to assist in planning and laying out the test procedure. This is also useful in determining if a layer can be detected by the seismic refraction technique. The general procedure is to enter the forward model, calculate, and then either plot the results or export them to the invMOD routines. The program calculates results consisting of the apparent velocities and intercept times for each layer. The program gives output for both the forward and reverse directions. If there is no dip angle for any of the interfaces, then the velocities and intercepts for both the forward and reverse directions will be the same.

```
****** SEISMO ******
Seismic Refraction Data Analysis and Presentaion Software
******** v2.7 Apr 90 ********
-----------------------------------------------------------------

To Select Menus Use: arrow keys
Menus: | FILE | PLOT | EDIT | invMOD | forMOD | RESULTS | SYSTEM |
Options:
        Input                           <<< select option
        Plot
        Export (vel & int to iMod)      enter Highlighted letter
```

Figure 21. Main menu (forMOD)

Input

56. When this option is selected, the control menu for forward model input will be displayed and it should appear as shown in Figure 22. This menu

is used to input the data necessary for the program to compute results of the forward model. The menu input fields are: the number of layers, the line length, distance interval to calculate arrival times, and the layer information. The individual sections of this menu will be discussed in detail in the following sections.

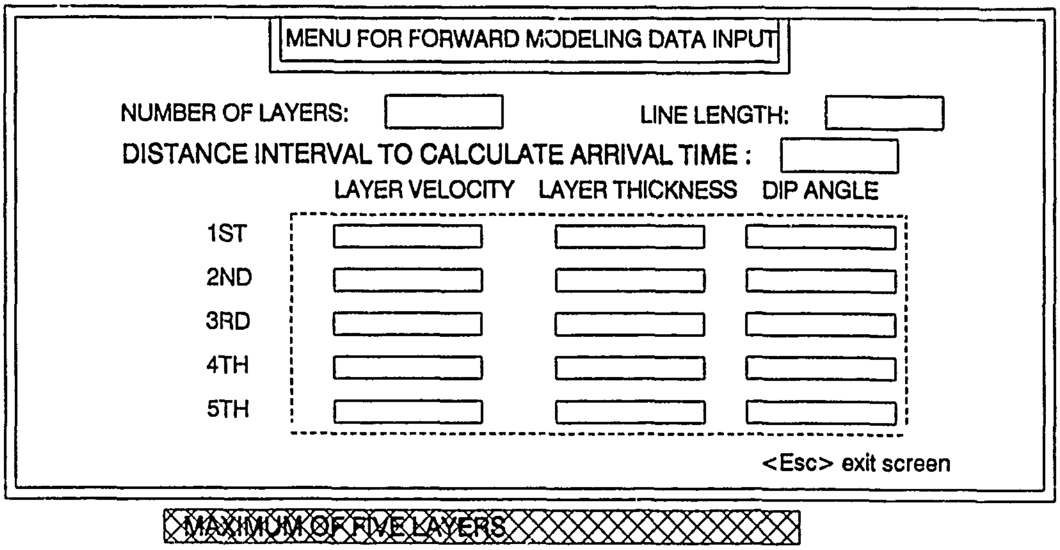


Figure 22. Menu for forward modeling data input

Number of layers and line length

57. This is the number of layers to be modeled and the length of the geophone spread. The program will handle up to five layers and any spread length. The line length is as described in paragraph 16.

Distance interval

58. This value is used by the routine to calculate corresponding arrival times over the length of the line at the selected interval. These calculations are based on the model input. If this value is left blank, then no arrival time calculation will be performed.

Layer information

59. The box in the center of the screen (Figure 22) contains the fields for inputting the layer information. There are three types of information for each layer; the layer velocity, the layer thickness and the dip angle. The layer velocity is the true velocity in feet or meters per second. The layer thickness is self-explanatory and entered in consistent units. The user

should not enter a thickness for the last layer, since that thickness is unknown. The dip angle is entered in degrees, and is taken as the angle of the layer interface from the forward end to the reverse end. A positive angle represents a downward slope, while a negative angle represents an upward slope. The dip angle for the first layer is that of the ground surface and is set by the program to be 0 deg. Most of the errors in using this routine come from entering too large a dip angle for the line length entered. See Appendix B for an explanation of forward modeling calculations. Upon exiting the routine, the calculation of the forward and reverse model will be performed and displayed on screen. The display will resemble Figure 25, with the input data being true velocities, depths to interfaces, and dip angles, and the calculated data being interface velocities and arrival times.

Plot

60. The plotter control menu should appear as shown in Figure 23. The options are the same as described in paragraph 28.

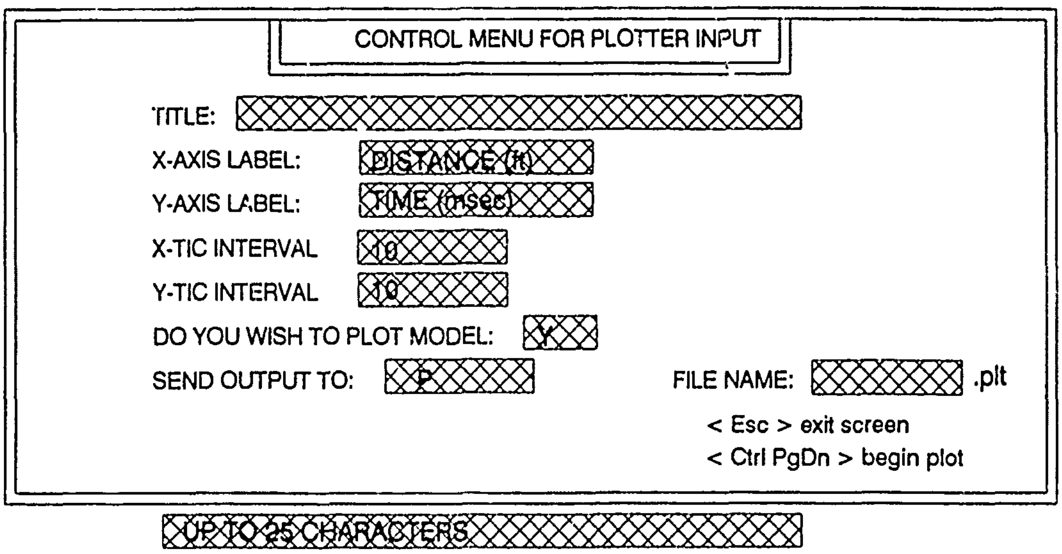


Figure 23. Plotter input menu

Export

61. This option is used to transport the calculated apparent velocities and intercepts into the inverse modeling routine. As such, the forward model input data must first be calculated; otherwise, there will be nothing to export. The program will print a warning if exportation is attempted before calculating. Exporting a forward model is a useful technique to give the user a starting inverse model that can be edited to best fit the data.

PART IX: RESULTS MENU

62. The results menu is the means of obtaining calculated output data from the program. The screen should appear as that in Figure 24. There are three options available from this menu; screen, printer, and final plate. Each one will be discussed in detail in the following sections. The results obtainable from the program are calculated results and can come from either the inverse or forward modeling routines.

```
                  ****** SEISMO ******
    Seismic Refraction Data Analysis and Presentaion Software
                ******** v2.7 Apr 90 ********
--------------------------------------------------------------
                To Select Menus Use:  arrow keys

 Menus:  | FILE | PLOT | EDIT | invMOD | forMOD | RESULTS | SYSTEM |
 Options:

        Screen                          <<< select option
        Printer                         enter Highlighted letter
        Final Plate
```

Figure 24. Results menu

Screen

63. This option presents a table of the calculated results from either the forward or inverse modeling routines to the screen. Figure 25 presents an example of such a screen. There are two blocks of information, one that contains the input data and one that contains the calculated results. If results from the inverse modeling routine are being displayed, then the input data will be apparent velocities and intercepts. The calculated results will be true velocities and depths to interfaces. If results from the forward modeling routine are being displayed, then the input data will be true velocities and depths to interfaces. The calculated results will be apparent

velocities and intercepts. The user presses <enter> to continue the program.

TITLE

*** INPUT DATA ***

LAYER #	FORWARD VEL ft/s	FORWARD TIME msec	REVERSE VEL ft/s	REVERSE TIME msec
1	500	0.0	500	0.0
2	2500	2.7	2500	2.5
3	5000	5.6	5000	5.5

*** COMPUTED SEISMIC PROFILE ***

LAYER #	TRUE VEL ft/s	DEPTH FOR ft	DEPTH REV ft
1	500		
2	2500	1.5	1.5
3	5000	3.0	3.0

PRESS < RETURN > TO CONTINUE ?

Figure 25. Example output to screen

Printer

64. This option sends the results to the printer. The printout will appear exactly as that described in the paragraph above and represented in Figure 26.

TITLE

*** INPUT DATA ***

LAYER #	FORWARD VEL ft/s	FORWARD TIME msec	REVERSE VEL ft/s	REVERSE TIME msec
1	500	0.0	500	0.0
2	2500	2.7	2500	2.5
3	5000	5.6	5000	5.5

*** COMPUTED SEISMIC PROFILE ***

LAYER #	TRUE VEL ft/s	DEPTH FOR ft	DEPTH REV ft
1	500		
2	2500	1.5	1.5
3	5000	3.0	3.0

Figure 26. Example output to printer

Final Plate

65. This consists of a plot of both the data and model as well as a listing of the calculated results. There is also a graphical representation of the resulting profile. This plot was designed to be used as a final figure in a report. When this option is selected, the program branches to the final plate plotter control menu. This menu is shown in Figure 27, and operates as described in paragraph 28. The only difference in this screen and that described in the above-mentioned paragraph is the absence of the plot model option. The model is always plotted and therefore it does not appear as an option in the plotter control menu for the final plate. An example of a final plate is shown in Figure 28.

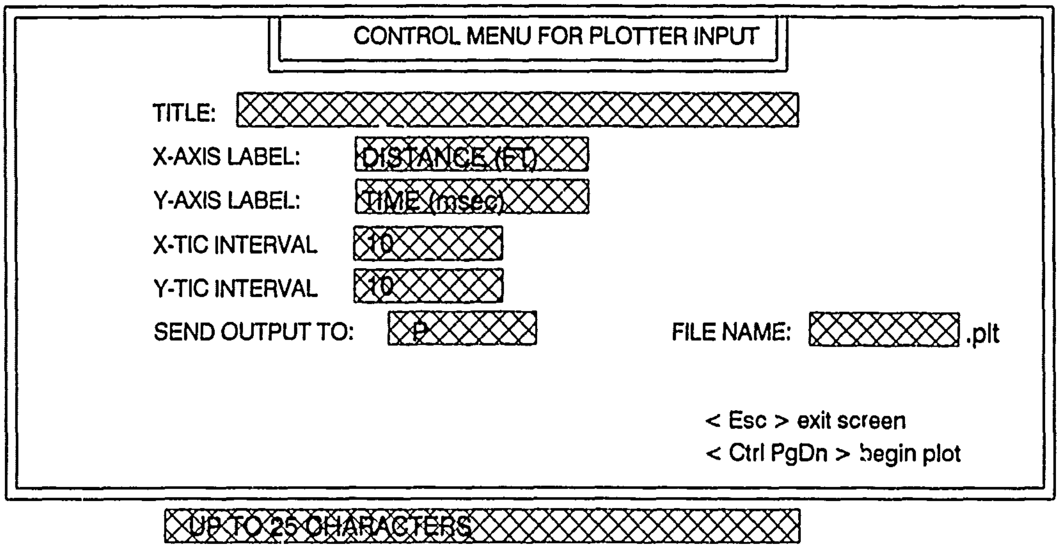
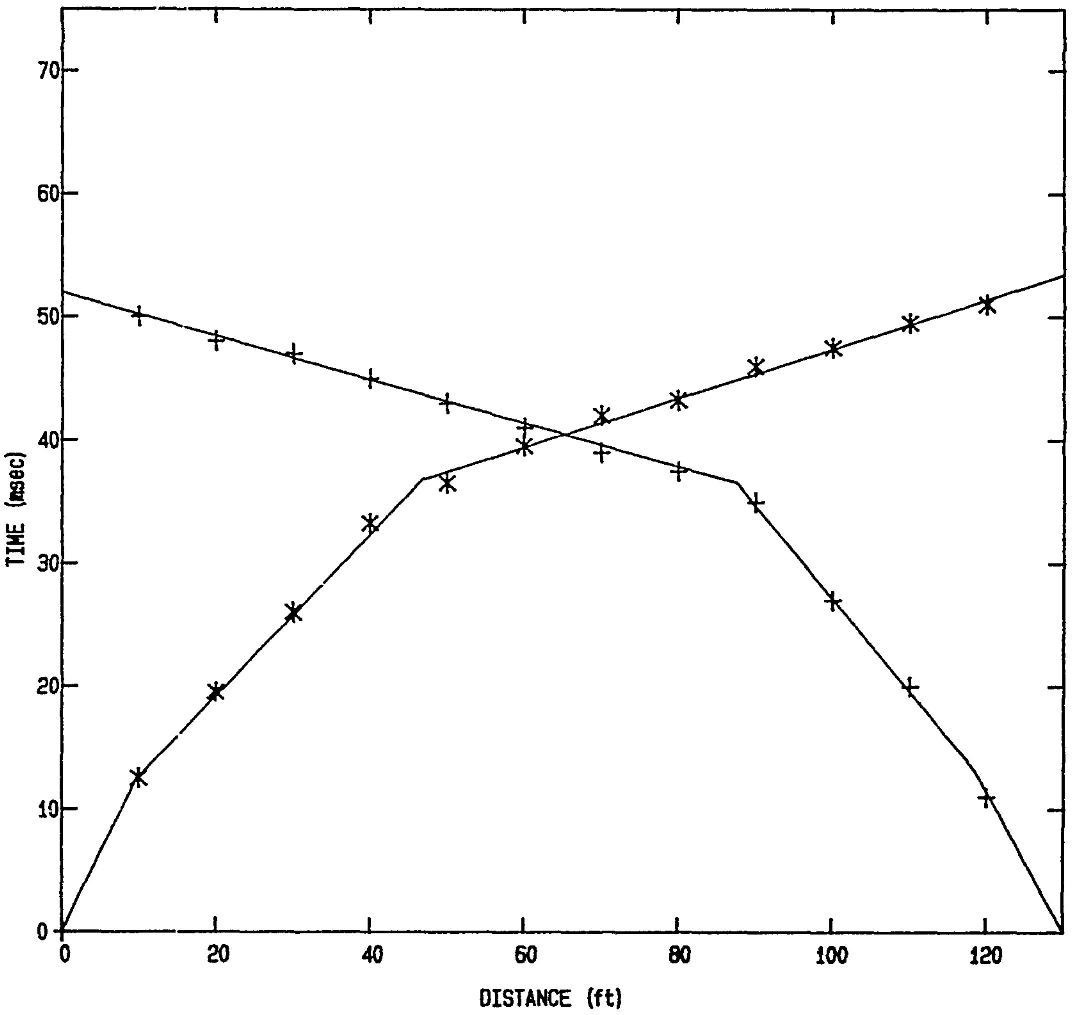


Figure 27. Control menu for final plate plot



EXAMPLE FINAL PLATE PLOT

**** INPUT DATA ****

layer #	forward vel ft/s	forward ti msec	reverse vel ft/s	reverse ti msec
1	783	0	875	0
2	1520	6	1325	4.5
3	5019	27.5	5677	29.1

**** COMPUTED PROFILE ****

Ground Surface

830

3 ______ 2.5

1410

18 ______ 19.5

5310

This layer extends to unknown depth

NOTE: All depths in ft
All velocities in ftps

Figure 28. Example final plate output

PART X: SYSTEM MENU

66. This menu contains options relating to the program environment and interfacing with the DOS operating system. The screen should appear as shown in Figure 29. There are four options available from this menu; quit, shell, help, and install. Each option will be described in detail below.

```
****** SEISMO ******
Seismic Refraction Data Analysis and Presentaion Software
******** v2.7 Apr 90 ********
--------------------------------------------------------------------------------
To Select Menus Use: arrow keys

Menus: | FILE | PLOT | EDIT | invMOD | forMOD | RESULTS | SYSTEM |
Options:

        Quit                              <<< select option
        Shell to DOS                      enter Highlighted letter
        Help
        Install
```

Figure 29. Main menu (System)

Quit

67. This option is used to conclude the SEISMO session and exit the program. This function will return control to the DOS operating environment. If no data file was written during the session, a warning will sound along with a question about quitting. This i to alert the user that data will be lost if the program is exited before saving the input data or model.

Shell to DOS

68. This option allows temporary exit from the program to perform DOS commands and then re-enter the program. The data are conserved while outside

the program. To return to the program, the user types exit and presses <enter>.

Help

69. This option will give on-line information, which is also contained in this manual. It is greatly reduced, but provides important information about movement within the main menu, selection of options, control menus, and inverse and forward modeling. The help information is presented in two screens. Instructions to exit the menu or proceed to the next menu are presented at the bottom of the screen. Screen one is shown in Figure 30, and screen two is shown in Figure 31.

Install

70. The install menu is used to change certain default parameters in the program. The menu is shown in Figure 32, and consists of the following fields; port for the plotter output, port for the printer output, and the units.

HELP MENU

* Move thru the main menu by using the <right/left> arrow keys

* Select options by typing the first letter of the option (red)

* Control menus
    - move between fields by pressing <enter>, <up/down> arrow keys
    - move to last field by pressing <PgDn>
    - move to first field by pressing <PgUp>
    - move within fields by using <right/left> arrow keys
    - all editing keys are active within a field
    - exit control menu by pressing <Esc>

<Esc> exit screen
<Ctrl PgUp> previous screen
<Ctrl PgDn> next screen

Figure 30. Help menu

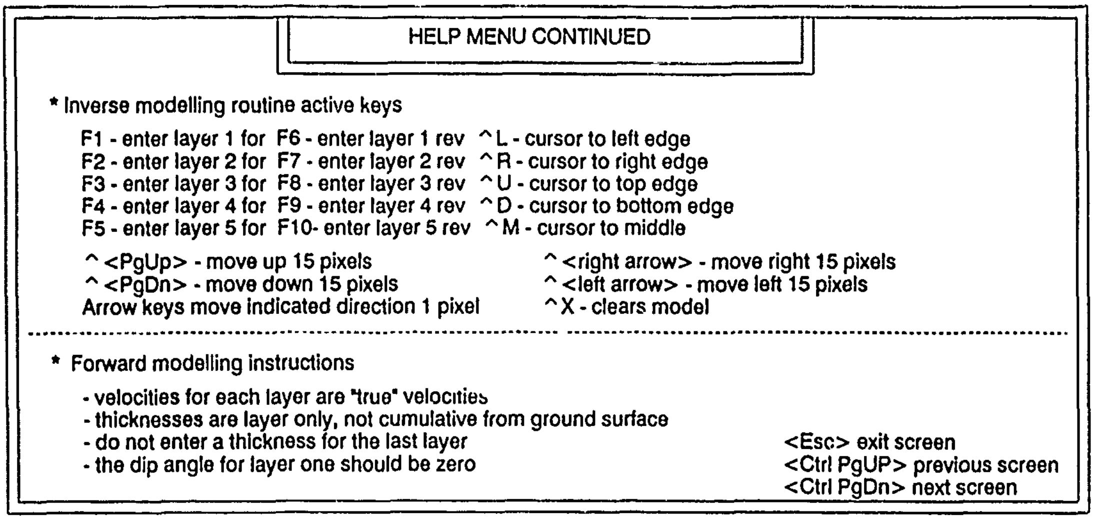


Figure 31. Help menu continued

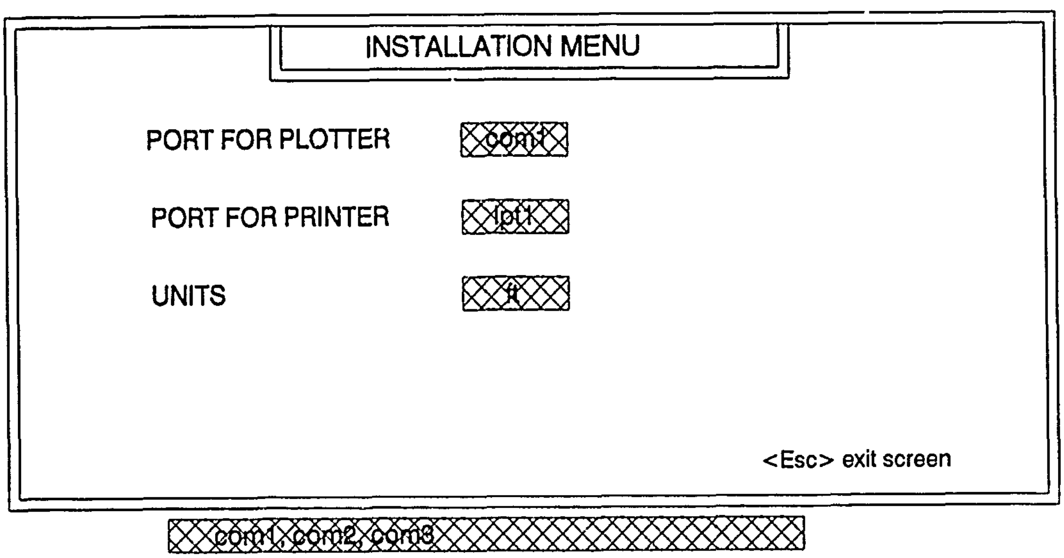


Figure 32. Install menu

APPENDIX A

FORWARD MODELING

Reference:

1. Butler, Gangi, Wahl, Yule, Barnes, 1982. Analytical and Data Processing Techniques for Interpretation of Geophysical Survey Data with Special Application to Cavity Detection, Miscellaneous Paper GL-82-16, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Ms.

EXCERPT FROM REFERENCE 1

Computer Modeling and Interpretation of Seismic Refraction Data

119. Two problems can be identified related to the seismic refraction method: (a) the direct problem, and (b) the inverse problem. The direct problem involves the determination of arrival times as a function of distance from a hypothetical source for various seismic events and a specified model; the model consists of layer velocities, layer thicknesses, and interface dips. For a given set of arrival time versus distance data from a refraction survey, the inverse problem involves the determination of the parameters of a subsurface model from the data itself. Two FORTRAN computer programs have been developed which solve the direct and inverse problems of the seismic refraction method, REFRDIR and REFRINV, respectively. REFRDIR is useful as a modeling tool for planning field surveys, e.g., geophone spacing and

survey line length required to investigate a possible subsurface model. REFRINV is very useful for refraction interpretation, where the data indicate the possibility of multiple, dipping layers.

120. The theoretical basis for the two programs (REFRDIR and REFRINV) is a set of equations relating to refracted waves (see, for example, Officer, 1957). These equations are given in the following sections describing the programs. They consist of: an equation for the horizontal phase velocity at the surface, equations corresponding to Snell's law at each interface, and an equation to compute the intercept times for the refracted waves.

121. Because the layer interfaces are assumed to be planar, the travel time for the wave refracted along the n^{th} interface (or top of the n^{th} layer) is given by

$$t_n(x) = T_{o,n} + x/v_n \tag{14}$$

Thus, given the horizontal phase velocity, v_n , and the intercept time, $T_{o,n}$ for the n^{th} refraction, the travel time can be computed at all source-to-receiver distances, x .

REFRDIR

122. The horizontal phase velocity and the intercept time are computed for each refraction event using the program REFRDIR. In this case, the P-wave velocities, the interface dips, and the layer "thick-nesses" must be given. This program gives the intercept times and the horizontal phase velocities for both the direct and the reverse profile. The reverse profile is that array layout in which the shot is on the opposite end of the array relative to the direct profile.

123. In computing the intercept times and the horizontal phase velocities, program REFRDIR uses the angles, $\theta^{\pm}_{in}$, that the rays make with the normals to the interface. These angles, as well as other important parameters (for example, the layer "thicknesses"), are illustrated in Figure 60.

124. REFRDIR is a modeling program. It assumes: (a) that the velocity variation in the earth increases monotonically with depth,

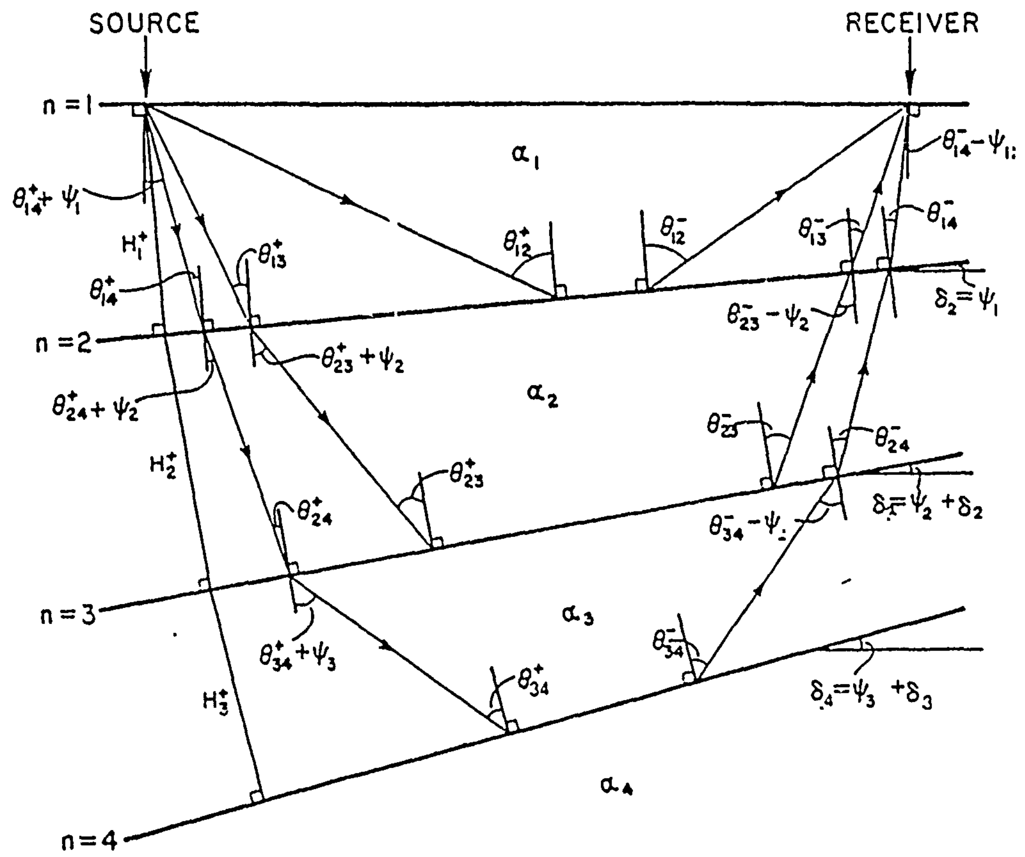


Figure 60. Assumed geometry for seismic refraction paths in common-strike, multiple dipping layers

(b) that it can be approximated by layers of constant velocity but with varying thicknesses, (c) that the interfaces between the layers are planar, and (d) that the interfaces have the same strike (see Figure 60). If REFRDIR is given an input model containing a velocity inversion (i.e., a decrease in velocity with depth), it will print an error message to that effect and stop.

125. The input data for the program are: (a) the number of layers in the model, (b) the layer thicknesses relative to the direct- and reverse-profile shotpoints (HPLUS and HMINUS; see Figure 1), and (c) the dip angles of the interfaces. The air/ground interface is the first one and it is assumed to be horizontal. Any velocity and distance

units may be used, as long as they are consistent, but the (dip) angles must always be given in degrees. REFRDIR computes and prints out: (a) the intercept times, and (b) the horizontal phase velocities of the refractions from each interface for the direct and reversed profiles. The following equations are used by REFRDIR:

$$\sin \theta_{n-1,n} = \alpha_{n-1}/\alpha_n \tag{15}$$

$$\theta_{n-1,n} = \theta^{+}_{n-1,n} = \theta^{-}_{n-1,n} \tag{16}$$

$$\sin \theta^{\pm}_{i-1,n} = (\alpha_{i-1}/\alpha_i) \sin (\theta^{\pm}_{i,n} \pm \psi_i) \tag{17}$$

$$v^{\pm}_n = \alpha_1/\sin(\theta^{\pm}_{1,n} \pm \psi_1) \tag{18}$$

$$T^{\pm}_{on} = (2H^{\pm}_{n-1}/\alpha_{n-1})\cos \theta_{n-1,n} + \sum_{i=1}^{n-2} (H^{\pm}_i/\alpha_i) (\cos \theta^{+}_{i,n} + \cos \theta^{-}_{i,n}) \tag{19}$$

The α's are the layer velocities, the H's are the layer thicknesses, the v's are the horizontal phase velocities, and the T's are the intercept times. The superscripts + or − refer to the direct and reversed profiles, respectively. See Figure 60 for the indexing and angle definitions.

126. For a given layer, computation is started by using Equation 15 to solve for $\sin \theta_{n-1,n}$. This, in turn, is used in Equation 17 to generate $\sin \theta^{\pm}_{n-2,n}$ through $\sin \theta^{\pm}_{1,n}$. The phase velocities and intercept times are then computed using Equations 18 and 19. To clarify the use of these equations, the calculations for the general case of three interfaces have been carried out in Appendix I. A listing of REFRDIR is also given in Appendix I.

127. Input. REFRDIR is extensively documented and prompting messages appear before each input. All input is in free-field format. The input sequence is given below:

Input No. 1: NLAYRS

NLAYRS--numbers of layers in the model

Input No. 2: SPRDLN

SPRDLN--the spread length, i.e., the length of the refraction survey line

Input No. 3: (ALPHA(N), DELTA(N), HPLUS(N), N=1, NLAYRS)

ALPHA(N)--velocity in layer N

DELTA(N)--dip angle (in degrees) of the N^{th} interface, which is the top surface of layer N ; DELTA (1) = dip of ground surface of model = 0

HPLUS(N)--thickness of N^{th} layer for the direct profile (see Figure 60)

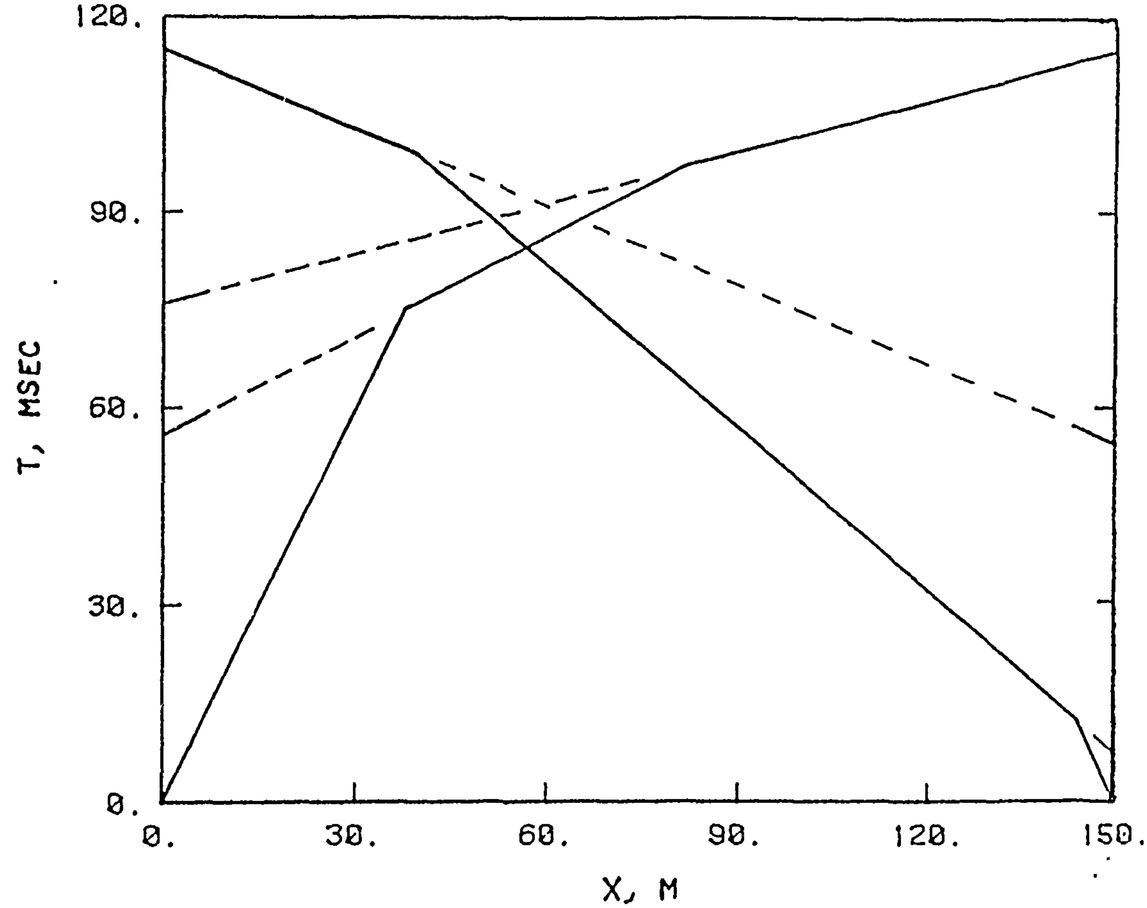
Input No. 3 is repeated for each layer.

Input No. 4:

Input "1" if only forward profile to be plotted, and input "2" to plot both forward and reverse profiles.

128. Output. REFRDIR output consists of tabulated and plotted versions of the results of the computation. The tabulated output gives the horizontal phase velocities (apparent velocities) and intercept times for the forward and reverse profiles. For the plotted output, the apparent velocities and intercept times are used to define line segments, and forward and reverse time-distance plots are produced. PLOT2 (Appendix B) is used to produce the plots.

129. Example. Figures 61 and 62 illustrate the use of REFRDIR to solve a direct seismic refraction problem. The hypothetical model is shown in Figure 61, and the spread length was selected as 150 m. Computed time intercepts, see Figure 62, are indicated on the plot in Figure 61. This example is important because it illustrates that intuitive predictions of interface dip from apparent velocities or of apparent velocities from dip may be incorrect. For the example in Figures 61 and 62, intuition and experience might lead one to expect that the apparent velocity in the forward direction for interface 3 would be greater than V_3 ; however, the results from REFRDIR (see Figure 62) show that this is not the case.



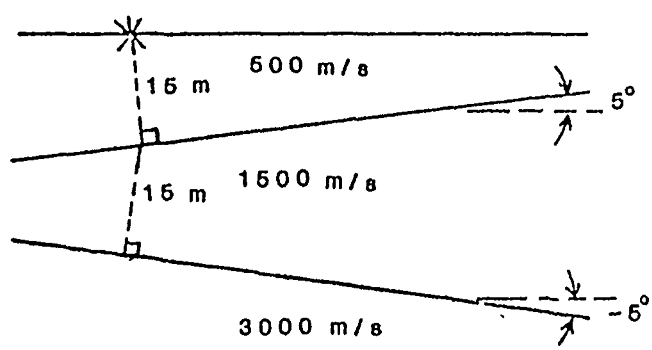


Figure 61. Three-layer model and first-arrival time-distance plot produced by REFRDIR

```
    INPUT NUMBER OF LAYERS IN MODEL
= 3

    INPUT LENGTH OF SHOT SPREAD
= 150

    FOR EACH LAYER INPUT A LINE ENTRY WITH THE FOLLOWING DATA
    SEPARATED BY COMMAS: LAYER VELOCITY,DIP OF INTERFACE,
    LAYER THICKNESS
=  500,0,15
= 1500,5,15
= 3000,-5,

    VELOCITIES ARE IN METERS/SEC (OR FT/SEC), TIMES ARE IN
    MILLISECONDS AND LAYER THICKNESSES ARE IN METERS (FT).

    THERE ARE 3 LAYERS IN THIS MODEL

    LAYER NO.      VELOCITY      DIP (DEGREES)      H+      H-
       1             500.           0.             15.0     2.0
       2            1500.           5.0            15.0    40.9
       3            3000.          -5.0

                   *****  CALCULATED RESULTS  *****

    THE HORIZONTAL PHASE VELOCITIES AND THE INTERCEPT TIMES FOR
    THE DIRECT (+) AND REVERSED (-) PROFILES.

    INTERFACE NO.      PHASE VEL+     PHASE VEL-      T+      T-
         2               2000.          1207.        56.6     7.5
         3               3896.          2498.        76.4    55.1
```

Figure 62. Tabular output from REFRDIR for case shown in Figure 61

APPENDIX B

INVERSE MODELING

Reference:

1. Department of the Army, 1979. Geophysical Exploration, Engineer Manual 1110-1-1802, Office, Chief of Engineers, Washington, D. C.

APPENDIX B
SEISMIC REFRACTION SURVEYING

B-1. Principle. The refraction method consists of measuring the travel times of compressional and sometimes shear waves generated by an impulsive energy source to points at various distances along the surface of the ground. The energy source is usually a small explosive charge or a sledgehammer blow. The energy is detected, amplified, and recorded so that its time of arrival at each point can be determined. The instant of the impact or explosion, the "zero time," is also recorded along with the ground vibrations arriving at the detectors (geophones). The raw data, therefore, consist of travel times and distances, the travel time being the interval between the zero time and the instant that the detector begins to respond to the disturbance. This time-distance information is then processed to obtain an interpretation in the form of velocities of wave propagation and structure of the subsurface strata. The process is illustrated schematically in figure B-1. All measurements are made at the surface of the ground, and the subsurface structure is inferred from interpretation methods based on the laws of wave propagation.

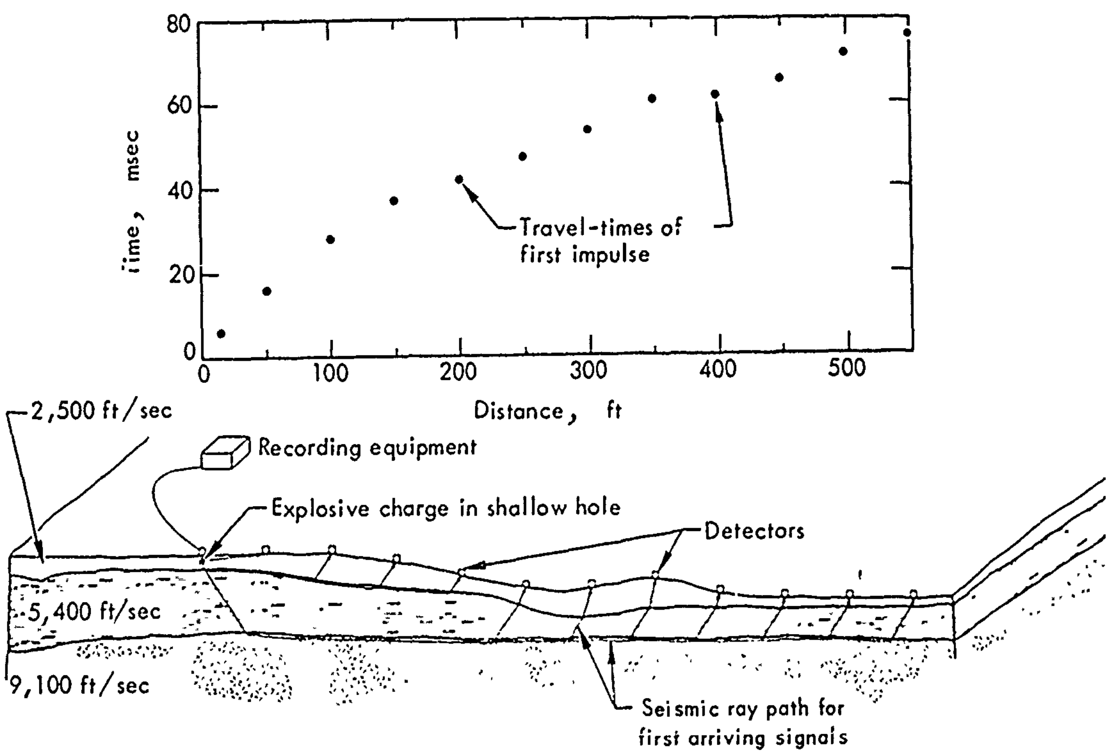


Figure B-1. Schematic of seismic refraction survey (after Redpath[20])

a. Wave Propagation in Elastic Media.

(1) A disturbance in an elastic medium propagates through two types of waves: compression waves, in which the deformations of the medium consist of alternating compression and rarefaction; and shear waves, in which the deformations of the medium are pure shear. At the surface of an elastic medium (ground surface), a third type of wave, a surface (Rayleigh) wave, is also generated. The amplitude of the displacements in a Rayleigh (R) wave is relatively large at the surface but dies out rapidly with depth. The compression wave is commonly called the "primary" wave, or the "P-wave," while the shear wave is called the "secondary," or "S-wave." In layered systems, other types of waves are generated along the boundaries between layers and resemble surface waves. However, they are not important to refraction surveys and are not considered in this manual.

(2) Fluids, or viscous media, differ from elastic media in that they cannot propagate S-waves, and only P-waves are observed directly.

(3) The P-wave is propagated at the highest velocity and is followed by S- and R-waves, in that order. As a result, the wave train received by a detector at a large distance from the source resembles that shown in figure B-2.

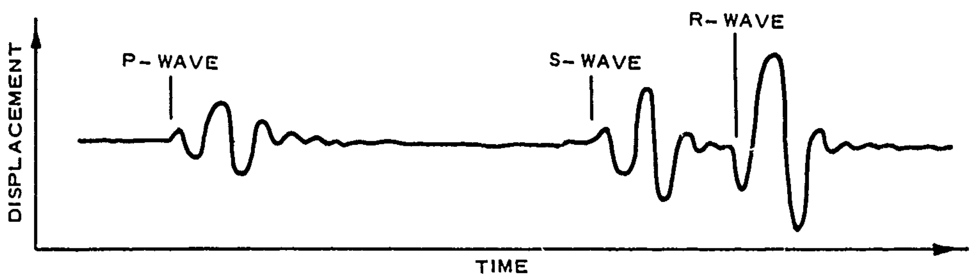


Figure B-2. Hypothetical wave train recorded by a geophone at the surface of a homogeneous elastic medium at some distance from the source (prepared by WES)

(4) In refraction surveying, only the P-wave is usually used. Thus, the travel time is determined by the arrival of the P-wave at the detector, or geophone. This is always the first arrival.

b. Refraction.

(1) General. The propagation of seismic energy through elastic media and across boundaries between layers is described by essentially

the same laws that govern the propagation of light rays through transparent media. According to Huygens' Principle, waves in a homogeneous medium radiate from a point source as expanding spheres, and every point on a wave front is the source of a new wave that moves away from it as an expanding sphere. Thus, a signal can travel between two points over an infinite number of different paths, each requiring a different amount of travel time. A <u>ray path</u> represents the shortest travel time and is thus the path of the first arriving signal. It is everywhere perpendicular to the wave front. The refraction or angular deviation that a ray undergoes when passing from one material to another depends upon the ratio of the transmission velocities of the two materials. The law that describes the refraction of light rays in terms of transmission velocities, known as Snell's law, also applies to the refraction of seismic waves in linear elastic media. This law, together with the phenomenon of "critical incidence," is the physical foundation of seismic refraction surveys.

(2) Refraction and reflection. When a P-wave meets a boundary between two media that have different elastic properties, <u>four</u> distinct new waves are generated at the point of contact. These new waves are: (a) a P-wave reflected back into the first medium, (b) a P-wave refracted in the second medium, and (c and d) similarly reflected and refracted S-waves. The newly generated S-waves, traveling at lower velocities than the P-waves, do not affect observations of first arrivals and can be ignored. The total energy in the four new waves is equal to that in the incident wave. However, since the energy of vibration is proportional to the square of the amplitude, the sum of the amplitudes of the reflected and refracted waves may be larger than the amplitude of the incident wave.

(3) Snell's law. Snell's law and critical incidence are illustrated in figure B-3, which shows a medium with a velocity v_1, underlain by a medium with a higher velocity v_2. According to Snell's law, the relation between the angle of incidence i of the incident P-wave and the angle of refraction r of the refracted P-wave is given by

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} \qquad \text{(B-1)}$$

where i and r are measured with respect to a perpendicular to the interface. More generally, this relation gives the directions of the ray paths for all four of the waves generated at the interface. If one substitutes for v_2 the velocity of either the P-wave or the S-wave in either of the two media, then r is the corresponding angle of reflection or refraction.

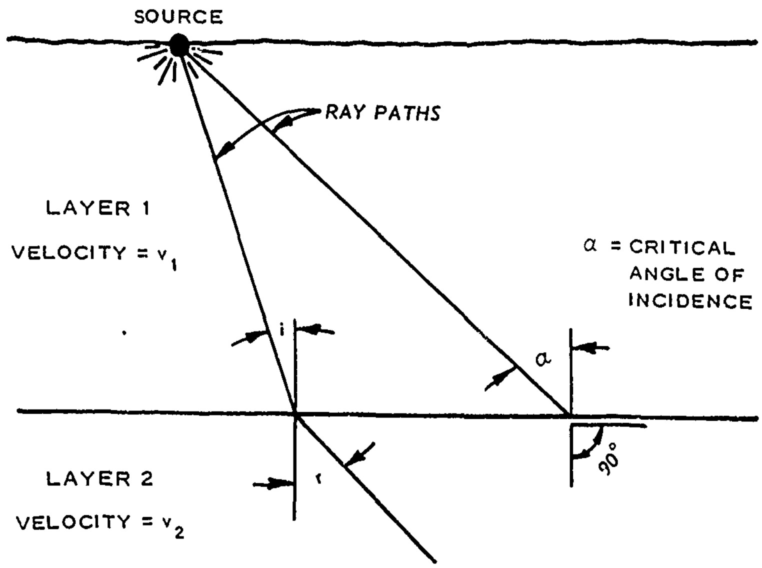


Figure B-3. Refraction of ray paths across a boundary between two elastic media (prepared by WES)

(4) Critical refraction.

(a) The critical angle of incidence α is the angle of incidence for which $r = 90$ deg, so that the refracted ray follows the boundary between the media. For angles of incidence smaller than the critical angle, most of the compressional energy is transmitted into the higher velocity medium. Where the angle of incidence is greater than the critical angle, the energy is almost totally reflected back into the lower velocity medium. At critical incidence, sin r is unity; so the critical angle of incidence is given by

$$\sin \alpha = \frac{v_1}{v_2} \qquad \text{(B-2)}$$

(b) The particular case of the critical angle of incidence is fundamental to the derivation of the formulas for refraction exploration. The critically refracted ray travels along the boundary between the two media at the higher of the two velocities, and it continually generates in the lower velocity layer seismic waves, called head waves, that depart from the boundary at the angle of critical incidence (i.e. are refracted back into the lower velocity layer). The angle of critical incidence may therefore also be called the angle of critical refraction.

(c) Figure B-4 is a wave-front diagram, showing the positions of the front of the disturbance at times t_1, t_2, t_3, and so on, as it propagates through a two-layer medium. The diagram shows that detectors at distances greater than some critical distance x_c from the source will receive the refracted signal (head wave) as the first arrival, while nearer geophones will first receive waves transmitted directly through the surface layer.

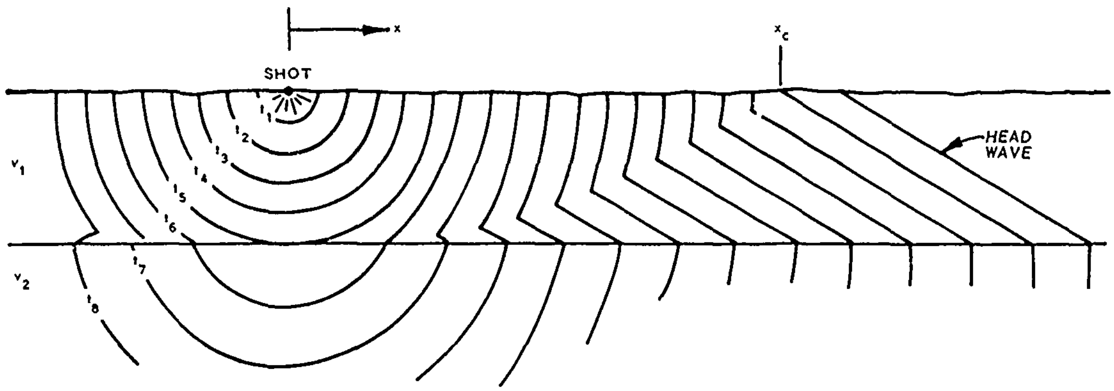


Figure B-4. Positions of wave front in a two-layer medium at times t_1, t_2,...(prepared by WES)

(d) The critical distance, often called "crossover distance" in the geophysics literature, can be identified from a plot of travel time of the first arrival versus distance (fig. B-5). For the simple, idealized case shown, the curve representing the direct wave is a straight line with a slope equal to the reciprocal of the velocity of the surface layer. For those ray paths refracted through the second layer, figure B-5 shows that the distance traveled in the surface layer is the same for all geophones. Therefore, the travel-time difference from one geophone to the next is the time required for the wave to travel in the lower layer along a horizontal path whose length is the same as the distance between the two geophones. The curve representing the refracted wave is thus a straight line with a slope equal to the reciprocal of the velocity of the wave in the second layer. The critical distance is indicated by the break in slope.

(5) Determination of layer thickness. At a point located exactly at the critical distance from the source, the direct and refracted waves arrive at the same time. One can write expressions for the travel times to this point by each of the two paths and, by equating the times, solve for the depth D_1 to the top of the second layer, in terms of x_c , with the following result:

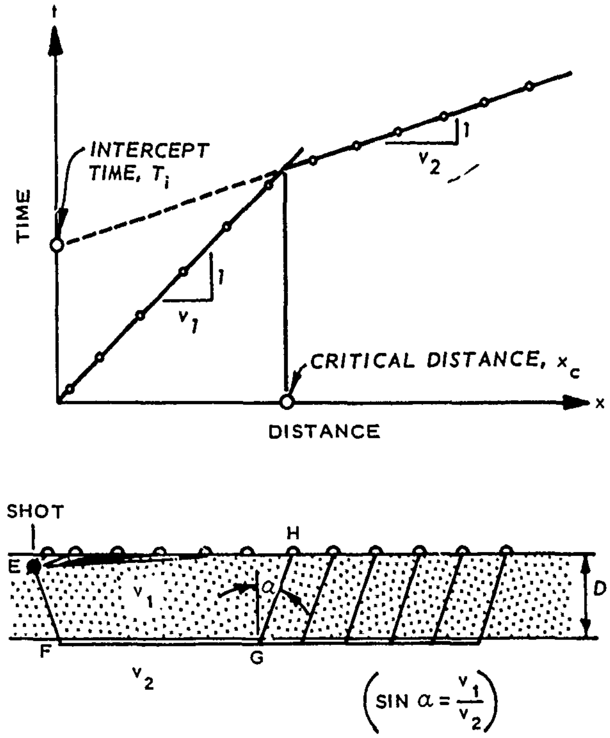


Figure B-5. Simple two-layer case with plane, parallel boundaries, and corresponding time-distance curve (after Redpath[20])

$$D_1 = \frac{x_c}{2}\sqrt{\frac{v_2 - v_1}{v_2 + v_1}} \qquad \text{(B-3)}$$

Equation B-3 is valid for the simple system shown in figure B-4 or B-5, i.e., a semi-infinite medium overlain by a single layer of lower velocity and uniform thickness, and for the depth to the first interface in a multiple-layer system. The actual field condition may be more complicated in several ways, such as irregular interfaces, dipping interfaces, and more complicated velocity distributions. The treatment of such cases will be discussed in paragraph B-4. In every case, it relies on the concepts of the path of the first arriving signal and of the critical angle of ray incidence.

B-2. Apparatus.

a. Seismic Units. A seismic unit consists basically of amplifier(s) and associated electronic circuitry, geophones, seismic cable, seismic energy source, blaster, if the energy source is an explosive, and recording device. The amplifier's function is to boost the signal detected by the geophones to a level suitable for input to the recording device. Sophisticated seismic units may include, in addition to amplifiers, filters (high-cut and low-cut), 60-Hz reject circuitry, a test circuit for geophone continuity, timebreak circuitry, and coarse and fine amplifier gain controls. Most seismic units are battery operated, either on 6 or 12 volts. Commercially available seismic units are many and varied; the choice of the best unit depends on the application for which it is intended and involves factors such as frequency of use, length of seismic lines, type of seismic source to be used, and the complexity of the anticipated project.

(1) Single or multichannel seismic units are readily available. Seismic units with more than 24 channels are not common but can be obtained on special order.

(a) The normal single-channel seismic units are very portable and easy to operate. They are used primarily with nonexplosive seismic sources and for seismic lines no longer than 100 to 150 ft. In some single-channel seismographs, "signal enhancement" is used to improve record quality. This is done by a memory circuit, which algebraically sums and stores the records of seismic signals produced by repeated operations of the seismic source. The repeated part of the record, which represents the useful signal, builds up with repeated summation, while random noise tends to cancel, so that the signal-to-noise ratio is improved. This feature improves performance in noisy environments and increases by about a factor of two the length of seismic lines that can be run with nonexplosive sources.

(b) Multichannel seismic units can either be very portable and simple to operate or otherwise, depending primarily on the amount of signal conditioning equipment included. Although multichannel units work well with either explosive or nonexplosive sources, the recording device that would ordinarily mate with the unit may impose limitations on the type of seismic source that can be used. Signal enhancement is also available for multichannel units. In addition, a test circuit for geophone continuity and the timebreak circuitry should be included on all multichannel units.

(2) In selecting a seismic unit, amplifier gains should be considered. A 90-decibel (db)* full-scale amplification is sufficient.

* A gain of 20 db signifies a ten-fold increase in the amplitude of the output signal over the input signal. A gain of 90 db, therefore, means an amplification ratio of $10^{4.5}$, or about 32,000, in signal amplitudes.

A signal that is too weak to be observed at 90 db generally cannot be distinguished from the ambient noise. Intermediate selection of gains from 0 to 90 db should be in steps no coarser than 6 db. The timebreak circuit should provide to the recording device a time break (zero-time) signal, which is obtained from the rupture (opening) of the bridgewire of the electric initiating device. Filters are particularly useful when seismic tests are conducted near high-voltage lines, machinery, or other sources of extraneous noises or motions. High-cut filters block out frequencies higher, and low-cut filters frequencies lower, than a chosen value. For example, if the low-cut filter is set at 25 Hz and the high-cut filter at 80 Hz, all signal components with frequencies below 25 or above 80 Hz would virtually be eliminated from the recorded signal. Three selections of filters on the low-cut side (such as 10, 25, and 45 Hz) and three on the high-cut side (50, 80, and 120 Hz) are usually sufficient.

(3) A geophone test circuit measures the coil resistance of each geophone. This provides for detection of such conditions as a loose connection between a geophone and the seismic cable, a foreign material (e.g., a sand grain) preventing proper contact between geophone and cable takeout, or a short circuit in the cable or geophone.

b. Recorders. The various display or recording devices may include timing lights for display of travel time in binary form, a direct digital readout of travel times, a seismic signal and time marker display on a cathode ray tube (CRT), or a recording of the time marker, seismic signal, and a set of timing lines on photographic film or oscillograph paper.

(1) Single-channel seismic units usually use timing lights, a direct digital readout, or a CRT display. Some recording devices with the CRT display have a camera attachment or a plug-in strip chart recorder so that a permanent record of the seismic signal can be obtained. Where timing lights or direct digital readouts are used, the only permanent record is in the field notes made by the operator.

(2) The recorders used with multichannel seismic units are oscillographs or magnetic tape recorders (analog or digital). An oscillograph normally includes: (a) a galvanometer for each recording channel; (b) an oscillator to produce timing pulses, displayed on the record as timing lines; and (c) in other than the simpler seismic units that make a record on a stationary photographic film, a paper drive with sensitized recording paper. The paper drive should be adjustable, so that at least two and preferably three recording speeds (about 15, 30, and 50 in./sec) are available. The speed adjustment is necessary to provide a time scale that is suitable for the types of site materials

and the geophone spacings used. Timing lines should be at intervals on the seismic record of not more than 10 msec.

(3) Galvanometers should have a broadband frequency response with a range of at least 0-300 Hz. On some seismic recorder systems, the galvanometers require periodic checks for alignment. This is done by activating the galvanometers with an externally supplied voltage pulse, obtaining a recording, and checking the time indicated by each galvanometer for the pulse. Any time differences noted in comparing the responses of all the galvanometers in the recorder indicate galvanometer misalignment, which can be corrected with an alignment tool.

c. Geophones.

(1) General. In refraction seismic surveying, geophones are generally vertically oriented, velocity-type transducers. The sensing elements usually consist of a magnet, rigidly attached to the geophone housing, and a surrounding spring-supported coil. Relative motion of the magnet and the coil produces an electrical signal. Firm contact with the ground is provided by a spike in the base of the geophone housing. A ground conductor may be included in the geophone and is desirable for use in environments (especially arid regions) in which static electricity may cause noise problems. Further, consideration should be given to sensitivity, durability, frequency response characteristics, damping, and impedance matching with the seismic unit. There are tradeoffs among these factors, and the best choice for a particular application usually involves some compromise. For example, the more sensitive a geophone is, the heavier and less durable it is.

(2) Sensitivity. A sensitivity of about 1.0 volt/in./sec is adequate for most refraction work and can be achieved in a geophone that is relatively rugged and light in weight.

(3) Frequency response. Natural frequencies of the geophones should range from 4.5 to 14 Hz (8-Hz average) and have a reasonably uniform frequency response up to about 300 Hz. At frequencies below the natural frequency, there is a sharp drop in the sensitivity; therefore, geophones should be selected on the basis of the lowest frequency that may have to be recorded. Good sensitivity to the higher frequencies is desirable because it contributes to the sharpness of the response to the first arriving seismic signal and thus to precision in picking the arrival times.

(4) Damping. Damping in a geophone shortens the time required for the coil to stop moving after the excitation ceases and so helps

to inhibit response to noise, but it also diminishes sensitivity. Generally, geophones for refraction work should be undamped.

(5) Impedance. Electrical impedance matching between geophone and seismic unit is required because a serious mismatch (more than an order of magnitude difference in impedance) will result in excessive signal loss at the interface. In most cases, geophones with coil resistances in the 100- to 1000-ohm range will provide satisfactory matching of impedance.

(6) Waterproofing. The geophone housing should be waterproofed; in addition, geophone connectors should not be vulnerable to damage by water and should be made of a rust-resistant material.

d. Seismic Cables. A seismic cable has a set of conductors that carry the electrical signals from the geophones to the seismic unit. The conductors are housed in a jacket that can be made of such materials as neoprene, rubber, plastic, or urethane. The number of conductors needed depends on the number of data channels (i.e. the number of geophones) to be recorded. This also dictates the number of takeouts (connection points for geophones) required on the cable. Takeouts should be waterproof and rust- and corrosion-resistant. The cable length, spacing and number of takeouts, and type of connectors on the ends of the cable can be specified by the purchaser. The cable should be at least 200 ft long between the connector and the first takeout on each end to ensure that sufficient distance can be placed between the seismic source and the seismic unit. Cables may be subjected to numerous detrimental effects, such as extreme heat and cold, water, snow, ice, abrasion (by rock, cactus, sagebrush, and other abrasive materials), and careless handling. Specifications for a seismic cable should include such characteristics as diameter, weight, flexibility, tensile strength, and resistance to temperature extremes, abrasion, scraping, cutting, tearing, cracking, and moisture. Seismic cables, as well as geophones, should have a ground conductor to minimize noise or cross-feed problems that may be encountered in arid regions.

e. Seismic Energy Sources.

(1) Nonexplosive sources. The energy for a seismic signal may be provided by sources such as a sledgehammer, a drop weight, air or gas guns, or a hydraulic force between an anchor and an inertial mass. Most commonly used are sledgehammers and drop weights, because of their simplicity and portability. They are usually used with a striking plate made of metal or wood. The time of impact (zero-time) is obtained from a microswitch attached either to the source or the striking plate, or from a geophone placed close to the point of impact. These sources deliver relatively little energy, as compared with explosives, and

seismic lines are generally limited to 100 to 200 ft in length (with corresponding depth of investigation about 30 to 70 ft). However, with the use of signal enhancement seismographs, this distance and depth range can probably be increased two-fold. Other types of nonexplosive seismic sources (air and gas guns, etc.) are more complex and require auxiliary equipment, such as air and gas tanks, compressors, and generators.

(2) Explosive sources. The performance of explosives is characterized primarily by strength (energy content), density, and detonation velocity. Strength refers to the percentage by weight of nitroglycerin (NG) in a straight dynamite (one which has only NG as the explosive) and usually ranges between 20 and 90 percent, the balance being primarily an inert absorbent, such as diatomaceous earth. Other explosives are given strength ratings referenced to the straight dynamite standard. The density of dynamites is commonly expressed as the number of 1-1/4- by 8-in. cartridges contained in a 50-lb case, which ranges from 85 to 205, while the density of other explosives is expressed in grams per cubic centimetre and ranges from 0.4 to 2.0. The detonation velocity is the velocity at which the shock wave of the explosion travels through a column of explosives, usually from 4,000 to 26,000 ft/sec for various kinds of explosives. These three properties contribute most to the force and power output of an explosive. To obtain P-wave data for engineering applications, the best performance will be given by explosives with the highest values of strength, density, and velocity. Generally, explosives can be categorized as dynamites, primers, and blasting agents, all of which are used extensively in refraction seismic work. In this application, electric devices are universally used to initiate the detonation.

(a) Electric initiating devices. These devices are the means by which the main explosives are initiated and the zero time is obtained. The primary types are electric blasting caps and exploding bridgewire detonators. Since accurate determination of the zero-time is extremely important in refraction seismic work, the initiating device should be instantaneous, i.e., there should be no time lag between the rupture of the bridgewire and the detonation of the device. Exploding bridgewire detonators (which require a special firing power supply) meet this criterion, as do instantaneous "seismograph-type" electric blasting caps. Either of these two types of initiating devices may be used satisfactorily in refraction seismic surveys, but delay caps should be avoided.

(b) Dynamites. Most dynamites are the NG-type, although some dynamites are non-NG. All dynamites are cap sensitive, i.e., they can be detonated by electric initiating devices. Their performance for refraction seismic test use ranges from poor to good. The user should refer to manufacturers' specifications to determine which dynamites have characteristics that are desirable in seismic use (strength, 50 to 90 percent; density, 110 cartridges or higher; and velocity, at least 14,000 ft/sec). Although dynamites are easily obtained and can be an excellent P-wave source, they have severe safety drawbacks, particularly the NG-type. For this reason, the use of dynamite for refraction seismic testing is not recommended. Unsafe characteristics of dynamites include sensitivity to shock and friction, very high flammability, and generation of toxic fumes. Other undesirable characteristics in most dynamites include low resistance to water (wetting desensitizes them so that they will not detonate) and susceptibility to freezing (upon thawing they become very unstable and dangerous to handle).

(c) Primers. Primers contain a relatively safe non-NG explosive and can be used to initiate noncap-sensitive explosives (blasting agents). They may also serve as the main explosives. All primers are cap sensitive, and their performance characteristics are excellent (strength, 60 percent and higher; density, 1.4 grams/cm^3 and higher; velocity, 20,000 ft/sec and higher). A common primer used in refraction seismic work is detonation cord. Explosive manufacturers' specifications should be consulted for the characteristics of various primers. Generally, primers are not as readily available as dynamites and are relatively expensive. Since their excellent performance and relative safety outweigh these factors, primers are highly recommended for refraction seismic work.

(d) Blasting agents. These products consist of a mixture of nonexplosive ingredients and, therefore, are not classified as explosives. They cannot be detonated by electric initiating devices but can be made to detonate by using high-strength primers. The performace of blasting agents as seismic sources ranges from poor to good; however, explosive manufacturers make a seismograph type of grade of blasting agent (commonly known as nitro-carbo-nitrate) that is satisfactory for seismic use. Manufacturers' specifications should be referred to for charteristics of blasting agents. The seismic-type blasting agents may not be as readily available as dynamites. However, they are considerably cheaper and much safer. For these reasons, they are recommended for seismic use, in conjunction with primers, when a main explosive consisting of more than 1 lb is required. A related product, available commercially under various trade names, is used frequently in refraction seismic testing. The product consists of two components, a flammable liquid (nitromethane) and a powder (ammonium nitrate), in separate containers. They are not classified as explosives until the components are mixed, shortly before being used; therefore, the two separate components may be transported and stored without restrictions. Safety tests conducted on mixed specimens yielded no detonations from impact or friction sensitivity, or rifle bullet tests, but the mixed product is cap sensitive, so that it can be detonated by electric initiating devices. A typical agent of this type has a strength of 70 percent, a density of 1.1 grams/cm^3, and a detonation velocity of 18,000 ft/sec. This product is highly recommended as an explosive source for refraction seismic work.

f. Blasters. A blaster is a device that provides an electrical pulse to initiate the detonation through an electric blasting cap. The best and most reliable blaster is the capacitive discharge type. Such a blaster uses dry cell batteries to charge a bank of capacitors, which then discharge the electrical energy to the detonator. The capacitive discharge blaster should deliver as much current (at least 0.5 amp) as is practically possible to the detonator. For seismograph-type electric caps, current should be from 0.5 to 4.0 amp. In addition to firing the detonator, the blaster also gives a timebreak output to the seismic unit. When the current from the blaster ruptures the bridgewire of the detonator and thus produces an open circuit, an electrical pulse is transmitted to the seismic unit and recorded as the zero time or time of detonation.

B-3. Field Procedure.

a. Layout of Seismic Surveys.

(1) Planning. Preliminary planning and design of a seismic survey should be done with due consideration of the objectives of the survey and the characteristics of the site. Important factors include topography, geology, the presence of noise generating activity, on-site utilities, hazards (such as power lines), structures, the depth of seismic investigation needed, and operational constraints (such as restrictions on the use of explosives). It is good practice to obtain as much of the relevant information as possible prior to mobilization of the field party and to make a systematic visual inspection of the site upon arrival. The best orientation of seismic lines is determined by the known geology of the site, topography (the ground surface should be as nearly level as possible), utilities (power lines, pipes, etc.), and the planned locations of the structures. The length of the seismic lines should be initially about four times the required depth of investigation but may be adjusted on the basis of early results. It is normal practice to run all lines in both a forward and a reverse direction to permit the detection of dip in the subsurface strata and to minimize the number of assumptions required in the interpretation of the data.

(2) Field layout. Prior to shooting, seismic lines should be marked with stakes at the shot points and geophone locations. Surveys

should be made to obtain the elevation of each shot point and geophone location and the azimuth of the line, and the location of the line should be tied to some well-defined feature on a map of the site. Accuracy of elevations and horizontal locations should be to within 0.5 ft or less. Elevations should be referenced to the project datum in every case except preliminary reconnaissance surveys, since correlation of seismically determined layer depths with boring information requires a common datum. In the case of reconnaissance surveys, it may be sufficient to refer elevations to an arbitrary datum (or a temporary bench mark) since only elevation differences, rather than absolute elevations, are required for interpretation. The seismic instrumentation, which is usually in a truck or van, should be at least 200 ft from each shot location, if explosives are used. It is also advisable for the equipment to be about 100 ft from the nearest geophone to minimize noise from movements of the operator or his assistants.

(3) Geophone spacing. Geophone spacing is determined primarily by the desired degree of definition of the subsurface layers and by the length of the seismic line. If the layers are relatively thin and the seismic lines are short, small geophone intervals are necessary; but if the layers are thick and seismic lines are long, greater distances between geophones are practical. On the basis of a 12-channel seismic system and seismic lines less than 200 ft long, geophone spacings from 10 to 15 ft would be sufficient. Seismic lines greater than 200 ft can be run with 25-ft geophone spacings. Only for seismic lines over about 1000 ft should greater geophone spacings be used, and then segments of the line should have 25-ft spacings. Very long seismic lines can be run in segments to avoid excessive distances between geophones. For example, if a 600-ft line is to be run with a 12-channel seismic system and 25-ft geophone spacings, the entire 600-ft line would first be staked with two shot points at each end. This spacing of the geophones, at 25-ft intervals from one end, would put the last geophone at 300 ft. A shot would than be fired at each end of the 600-ft line to obtain one segment in both forward and reverse directions. The geophones would then be moved to cover the remaining 300 ft, and the other two shots would be fired to obtain the second segment of the total line. Where the seismic line is long, particularly if geophone spacings are 25 ft or more, auxiliary short lines with small geophone spacings should be run along the primary line, at each shot point location and in the middle of the line, to provide more information on the near-surface materials. For simplicity, the primary seismic lines are generally run with equal geophone intervals.

b. Conduct of Tests.

(1) Mechanical energy sources. Because of their relatively

low energy output, nonexplosive sources are used primarily in shallow exploration and for S-wave velocity surveys. Usually a sledgehammer is used with a wood or metal striking plate. If a zero-time device is not attached to the seismic source, the striking plate should be as close as possible to the geophone on the end of the line. After a record is obtained, the striking plate is moved to the opposite end of the line, and the procedure is repeated to obtain the reverse record.

(2) Explosive energy sources.

(a) Shot holes. If explosives are used, shot holes are required to contain the energy of the explosive in the ground and for the safety of personnel. The holes are usually drilled by hand augers. They should be from 2.5 to 6 in. in diameter and usually from 3 to 10 ft deep, depending on the size of the explosive charge. A 3-ft-deep hole will usually contain the energy (prevent blowout of material) from a 1-lb charge, and a 10-ft-deep hole can contain the energy of a 10-lb charge, depending on geological conditions. After the armed charge is placed in the shot hole, soil material, preferably sand, is used to backfill the hole. Some materials may require tamping to ensure that as much material as possible covers the charge. Backfilling helps to contain the energy in the soil and is a safety factor in that it aids in preventing ejection of debris from the shot hole.

(b) Test procedure. Any person using explosive materials should be cognizant of the hazards that may be caused by faulty or careless handling of these materials. Regulations of Federal, state, and local governments govern the storage, transportation, and use of explosive substances, and the qualifications of personnel who use them. The operator should follow all applicable regulations and should be fully qualified. Following regular, systematic procedures during seismic surveys helps to assure the safety of persons and property and the acquisition of good data. The normal procedure for a seismic test is as follows:

Step 1. The shot holes are prepared.

Step 2. Firing lines are run from the blaster to each shot point, and each firing line is shorted at the blaster end.

Step 3. The external shorting plug (a plug that is inserted in the blaster to complete the firing circuit) is removed from the blaster and is held by the person who is to arm the charge.

Step 4. One of the firing lines is connected to the blaster.

Step 5. The weather conditions are evaluated for the possibility of thunderstorms in the next hour; if no danger exists, the area is cleared of personnel and vehicles and radio transmission is stopped. If the weather is adverse, the sequence is delayed until conditions improve.

Step 6. The unarmed explosive charge and detonator are carried separately from the approved storage location to the shot point by the person who is to arm the charge and an explosive handler.

Step 7. A blasting galvanometer is used to check the resistance of the detonat [illegible] the firing line is shorted.

S[illegible] aced in the shot hole, and the hol[illegible]d

Step 9. The [illegible] and firing line are again checked with the blasting galvanometer, and the detonator lead wires are tied to the firing line.

Step 10. The firing line should be secured near the mouth of the borehole to eliminate the possibility of its being carried by the explosion into an overhead hazard, such as a high-voltage power line.

Step 11. Amplifier gains are adjusted to minimize background noise. Gains are usually adjusted so that those for the geophones nearest the shot are relatively low. High gains on these amplifiers may result in saturation of the system and cross-feed between channels.

Step 12. The area of the shot is cleared, and the person who has armed the charge then gives the external shorting plug to the operator, who places it in the blaster.

Step 13. The operator checks to see that the recorder is on, fires the charge, and secures the record.

Step 14. The blaster verifies that detonation has occurred; when it is judged safe, he enters the area alone while being watched by another crew member, checks for any explosive that might not have been detonated, and if none is present, gives an "all-clear" signal.

c. Sources of Problems. In some instances, problems are encountered in refraction work that lead to degradation of data quality. These may include:

(1) Background noise. If wind noise is troublesome, it can be minimized by burying the geophones. Machinery noise can sometimes be

eliminated by electrically filtering the output of the geophones.

(2) Lack of seismic energy coupling. Deeper shot holes and better backfilling procedure may help to minimize this problem. The shot hole could be too large in proportion to the diameter of the explosive and thus produce voids at the point of the shot.

(3) Wet weather. Geophones and cable should be waterproof. Because connectors on either end of the seismic cable are not usually waterproof, they must be protected by water-resistant covers, such as plastic bags or polyethelene film. Water in one of these connectors may cause cross-feed and 60-Hz interference. Impact of rain on the geophones may cause high noise levels on the seismic records and can mask the true signals. Field operations should cease when any lightning is present in the area.

(4) Improper placement of geophones. This is a common problem and is usually caused by carelessness. The result is excessive background noise on the record and poor detection of the seismic signal. The location of the geophone should be cleaned of any vegetation, and the spike on the geophone should be pushed firmly into the ground to make the contact as tight as possible. Many times, the top 2 or 3 in. of soil is very loose and should be scraped off so that the geophone can be implanted into firm soil.

(5) Frozen ground. A frozen surface layer will give erroneously high values of velocity (approximately 6000 ft/sec) for the near-surface material.[64] The problem can sometimes be overcome by breaking up the frozen ground with a pick, provided it is not excessively thick.

(6) Metallic tapes. If metallic measuring tapes are used for the layout of seismic lines, they should be taken up before shooting. If left in place, they may provide a high-velocity short-circuit path for the seismic signal, giving spurious high-velocity values for the soil.

B-4. Interpretation.

a. General. If a particular set of subsurface conditions is postulated, including thicknesses, geometry, and velocities, a theoretical time-versus-distance plot can always be constructed. However, the inverse of this process is not generally possible. For a given time-distance plot, the interpreter cannot infer a uniquely possible set of subsurface conditions. Because of this difficulty, conventional interpretation methods rely on the use of hypothetical, idealized models, such as the simple two-layer case with a horizontal interface and $v_1 < v_2$, the multiple-layer case with horizontal boundaries and velocities increasing with depth, or more complicated alternative models that may include fault offsets, dipping strata, and the like. The model chosen is the one whose hypothetical time-distance plot most nearly matches the field data.

b. Two-Layer Case. Figure B-5 illustrates the simple two-layer case, with plane, parallel boundaries, with velocities uniform within each layer, and with the deeper layer having a greater velocity than the surface layer. The upper boundary represents the ground surface. As shown, the boundaries are horizontal, but the seismic response is exactly the same for inclined, parallel boundaries. For such a case, it is necessary only to observe that depths or thicknesses determined in refraction surveys are always measured normal to the layer boundary and are not necessarily vertical. The velocities v_1 and v_2 of the two layers are determined from the slopes of the two straight-line segments on the time-distance plot, the velocity being equal to the reciprocal of the slope. The layer velocity may be computed from the time and distance intervals, Δt and Δx , between any two points on the line segment corresponding to the layer. Thus,

$$v = \frac{\Delta x}{\Delta t} \qquad \text{(B-4)}$$

c. Critical Distance. The critical distance x_c can be picked from the intersection of the two straight-line segments. The depth D_1 to the second layer is given by equation B-3, which is repeated here for convenience:

$$D_1 = \frac{x_c}{2}\sqrt{\frac{v_2 - v_1}{v_2 + v_1}}$$

d. Intercept Time. An alternative method of interpretation is provided by the intercept time T_i , which is the intercept of the second line segment on the time axis, as shown in figure B-5. The depth D_1 can be expressed in terms of the intercept time as

$$D_1 = \frac{T_i v_1 v_2}{2\sqrt{v_2^2 - v_1^2}} \qquad \text{(B-5a)}$$

An equivalent form of this equation is

$$D_1 = \frac{T_i v_1}{2 \cos \alpha} \qquad \text{(B-5b)}$$

where α is the critical angle of incidence, defined by Snell's law, as in equation B-2. To obtain the result in this form it is helpful to note that since the critical angle of incidence α is given by $\sin \alpha = v_1/v_2$, one can write

$$\cos \alpha = \sqrt{1 - \left(\frac{v_1}{v_2}\right)^2} \tag{B-6}$$

and

$$\tan \alpha = \frac{\frac{v_1}{v_2}}{\sqrt{1 - \left(\frac{v_1}{v_2}\right)^2}} \tag{B-7}$$

In practice, the intercept time is usually more convenient to use than the critical distance, although the two methods are completely equivalent. The critical distance method offers two advantages: (1) travel-time errors that affect all geophone records equally (such as a blasting cap delay) do not affect the critical distance or the apparent velocities, and (2) the critical distance is useful in estimating the length of the seismic line required to detect a subsurface layer at a particular depth.

e. Critical Distance Versus Depth. Equation B-3 can be used to construct a graph showing the length of a seismic line (relative to the depth of the first layer) required to detect refractions from the underlying layer, as a function of velocity ratios. As shown in figure B-6, this can be useful in planning a seismic survey if velocity ratios can be estimated. The graph is also helpful in illustrating the effect of velocity contrasts. For example, assume that there is about 15 ft of overburden with a velocity of 2500 ft/sec, and that it is underlain by a shale with a velocity of about 5500 ft/sec. How long should the seismic line be to ensure adequate coverage for mapping the overburden thickness? If the velocity ratio v_2/v_1 is 2.2, then x_c/D_1 is approximately 3.25 and x_c is about 50 ft. The line should be at least 60 ft long to assure that x_c is well defined by the time-distance plot.

f. Multiple-Layer Case.

(1) Figure B-7 illustrates a simple multiple-layer case. It is assumed that the layers have plane, parallel boundaries (including the ground surface), velocities are uniform within each layer, and layer velocities increase with depth. The time-distance plot has a line

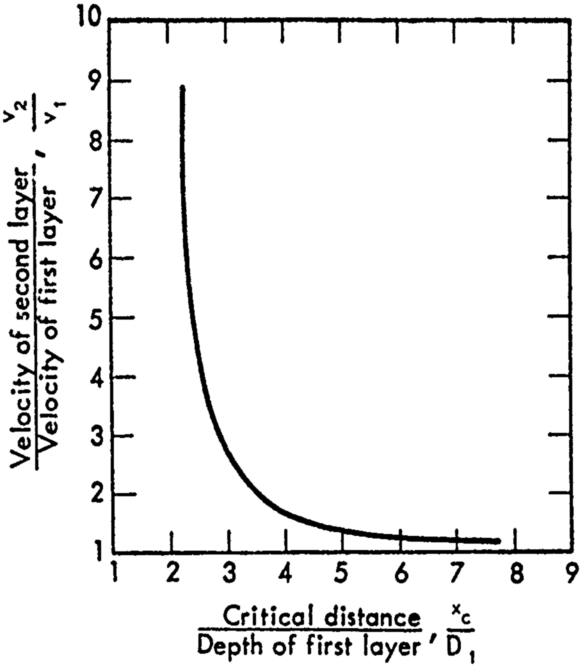


Figure B-6. Plot of ratio of critical distance to depth of first layer as a function of velocity contrast (after Redpath[20])

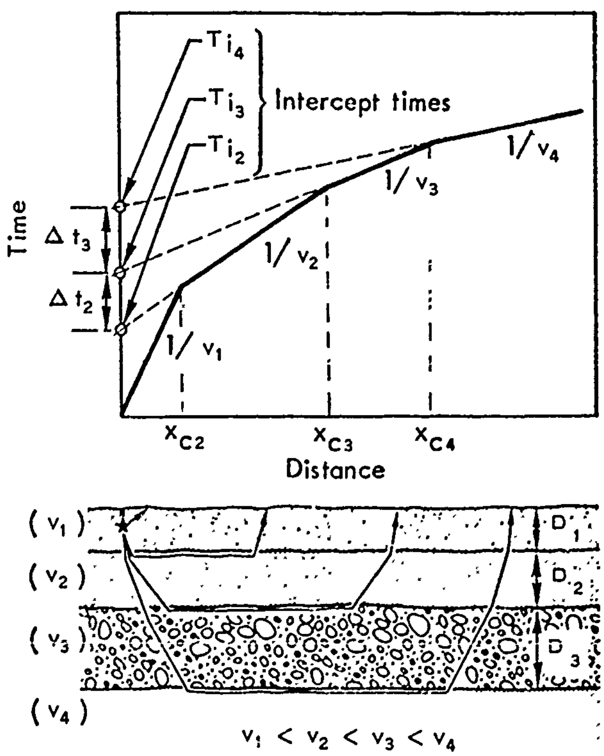


Figure B-7. Schematic of multiple-layer case and corresponding time-distance curve (after Redpath[20]) segment corresponding to each layer and having a slope equal to the reciprocal of the layer velocity. Each interface has a critical distance and a corresponding intercept time. In figure B-7 and in the equations below, the subscript identifying the critical distance and intercept time is that of the layer lying immediately below the interface.

(2) The thickness D_1 of the first layer is found by using the two-layer case and either the intercept time T_{i2} of the second line segment or the critical distance x_{c2} determined by the first two line segments. This thickness is used in computing that of the next lower layer, D_2 , as follows:

$$D_2 = \frac{T_{i3} V_2 V_3}{2\sqrt{V_3^2 - V_2^2}} - D_1 \left(\frac{V_2}{V_1}\right) \sqrt{\frac{V_3^2 - V_1^2}{V_3^2 - V_2^2}} \qquad \text{(B-8)}$$

The equivalent of equation B-8, in terms of critical distance, is

$$D_2 = \frac{x_{c3}}{2} \sqrt{\frac{V_3 - V_2}{V_3 + V_2}} + \frac{D_1}{V_1} \left(\frac{V_3 \sqrt{V_2^2 - V_1^2} - V_2 \sqrt{V_3^2 - V_1^2}}{\sqrt{V_3^2 - V_2^2}} \right) \qquad \text{(B-9)}$$

The computation can be extended to deeper layers by use of either of the general equations

$$D_n = \frac{T_{in+1} V_n V_{n+1}}{2\sqrt{V_{n+1}^2 - V_n^2}} - \sum_{j=1}^{n-1} D_j \left(\frac{V_n}{V_j}\right) \sqrt{\frac{V_{n+1}^2 - V_j^2}{V_{n+1}^2 - V_n^2}} \qquad \text{(B-10)}$$

and

$$D_n = \frac{x_{cn+1}}{2} \sqrt{\frac{V_{n+1} - V_n}{V_{n+1} + V_n}} + \sum_{j=1}^{n-1} \frac{D_j}{V_j} \left(\frac{V_{n+1} \sqrt{V_n^2 - V_j^2} - V_n \sqrt{V_{n+1}^2 - V_j^2}}{\sqrt{V_{n+1}^2 - V_n^2}} \right) \qquad \text{(B-11)}$$

in which D_n is the thickness of the n^{th} layer. Since the equations in this form contain the thicknesses of shallower layers, the computation begins with the first layer and progresses downward. Equations

B-10 and B-11 can be used to obtain equations for cases with particular values of n , or they may be used in the general form in computer codes for processing seismic data.

g. Two-Layer Case with Dipping Interface.

(1) The geometry of this case and the corresponding time-distance plot are presented in figure B-8. In developing the model for this

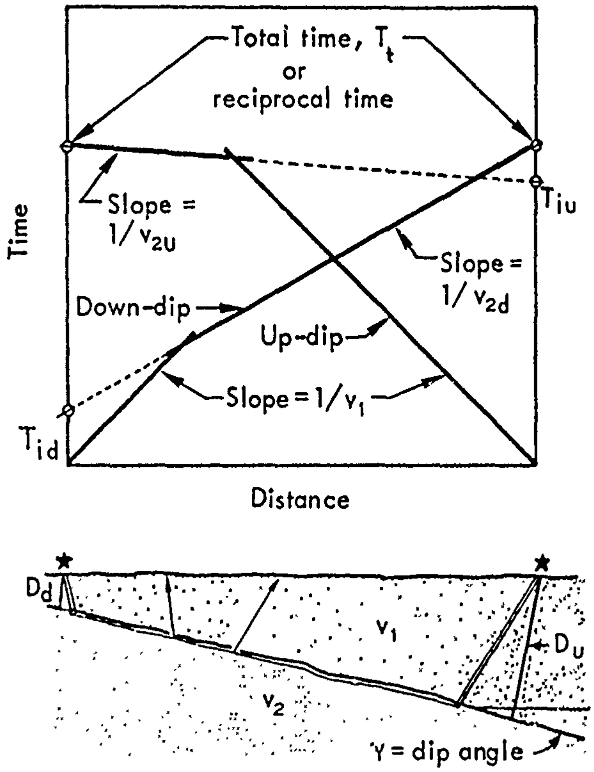


Figure B-8. Example of dipping interface and concepts of "reverse shooting" and "apparent velocity" (after Redpath[20])

case, assume that the interface between layers 1 and 2 is a plane dipping at an angle γ with the ground surface, that the velocities are uniform within layers, and that v_2 is greater than v_1 .

(2) It is not possible with a shot in only one direction along a seismic line to determine whether the interface is parallel to the ground surface or not; moreover, if the interface does dip, the slope of the time-distance curve does not give the true velocity for layer 2.

For these reasons, refraction seismic lines should always be run in both forward and reverse directions, i.e. with a shot point at each end of the line.

(3) The diagram in figure B-8 shows a shot point at each end of the seismic line, as used in reverse shooting, and also the ray path of the shortest travel time between the ends of the line. This path lies in a plane normal to the plane of the interface, and the cross section of figure B-8 is in the same plane. The distances D_u and D_d are the perpendicular distances from the two shot points to the plane of the interface. To avoid confusion, and to maintain consistency, the subscript u is used where the seismic line extends up-dip from the shot point, and d when the seismic line extends down-dip from the shot point. Thus, the distance D_d refers to the shot point located at the up-dip end of the line, and D_u to the shot point located at the down-dip end of the line.

(4) The angle γ in figure B-8 is the apparent dip, or the component of dip in the plane of the figure. It is very close to the true dip angle δ of the interface if the seismic line is laid out within about 10 deg of the direction of the true dip.

(5) The time-distance plot is made by plotting in both directions with each shot point in turn as the origin. As noted in the plot (fig. B-8), the velocity of the surface layer is correctly represented by the reciprocal slope of the first line segment, but the apparent velocity of the second layer is different for the two directions. The critical distance also depends on whether the shot point is at the up-dip or the down-dip end of the line. The total travel time T_t from one end of the line to the other, however, must be the same for both directions, since this time merely represents travel in opposite directions along the same path. This time is sometimes called the reciprocal time. Any disparity in the reciprocal time is an indication of a mistake in data, plotting, computation, or layout of the line.

(6) The effect of the dip on the apparent velocity can be seen by observing that the path of the first arrival is determined by the critical angle of incidence, as given by Snell's law, and for a given shot point, the length of the travel path in the upper (low-velocity) layer is different for each geophone location. With the shot point at the up-dip end of the line (shooting down-dip), the travel path in the upper layer becomes increasingly longer for more distant geophones, and the resulting apparent velocity of layer 2 is lower than the true velocity. With the shot point at the down-dip end of the line (shooting up-dip), the reverse is true and the apparent velocity is greater than the true velocity.

(7) It is relatively simple to write an expression for the travel time T_u or T_d to any geophone from either shot point and to find the derivative dT_u/dx or dT_d/dx, which is equal to the slope of the time-distance plot. If the respective slopes are denoted m_u and m_d, the following relations apply:

$$m_u = \frac{1}{v_{2u}} = \frac{1}{v_1} \sin (\alpha - \gamma) \tag{B-12a}$$

$$m_d = \frac{1}{v_{2d}} = \frac{1}{v_1} \sin (\alpha + \gamma) \tag{B-12b}$$

where α is the critical angle of incidence according to Snell's law, and the other quantities are as shown in figure B-8. Equations B-12a and B-12b can be rewritten to solve for the angles α and γ, as follows:

$$2\alpha = \sin^{-1} v_1 m_d + \sin^{-1} v_1 m_u \tag{B-13a}$$

$$2\gamma = \sin^{-1} v_1 m_d - \sin^{-1} v_1 m_u \tag{B-13b}$$

The perpendicular distances from the shot points to the interface are given in terms of intercept times by

$$D_u = \frac{v_1 T_{iu}}{2 \cos \alpha} \tag{B-14a}$$

$$D_d = \frac{v_1 T_{id}}{2 \cos \alpha} \tag{B-14b}$$

(8) The velocity v_2 can be computed from v_1 and the critical angle α, according to Snell's law (equation B-2):

$$\sin \alpha = \frac{v_1}{v_2}$$

Alternatively, it can be computed from the relation

$$v_2 = \left(\frac{2v_{2u} v_{2d}}{v_{2u} + v_{2d}} \right) \cos \gamma \tag{B-15}$$

Where the dip is small, $\cos \gamma$ is nearly equal to unity, and an approximation for v_2 that is good enough for most cases can be computed by taking $\cos \gamma$ equal to 1.

(9) Since the angle γ is an apparent dip angle, which depends on the direction of the seismic line relative to the direction of dip, two seismic lines in different directions are required if the true dip is needed. Each line must be shot in both forward and reverse directions.

(10) In figure B-9, the lines 0-1 and 0-2 are two seismic lines, and the angle between them is denoted by θ . Lines 0-d and 0-s are

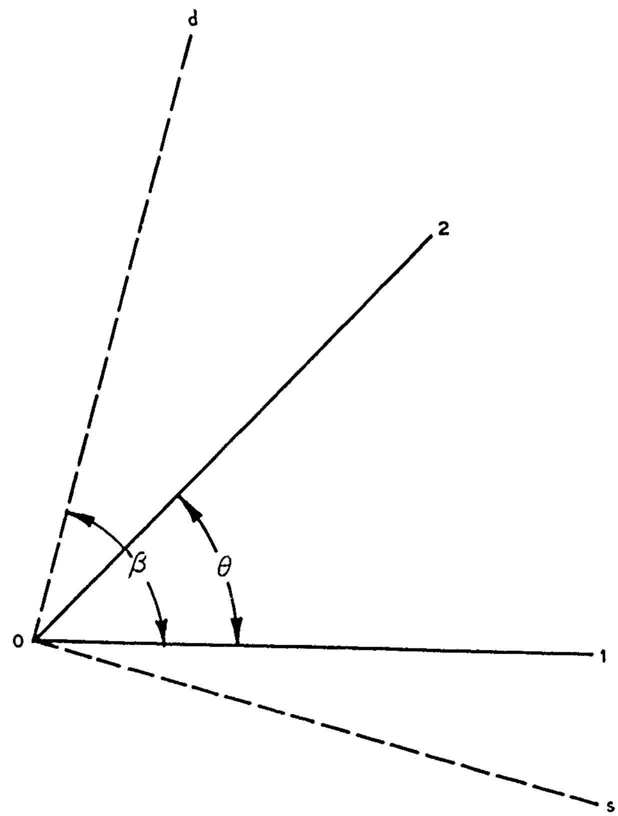


Figure B-9. Determination of dip and strike by two seismic refraction lines (prepared by WES)

in the dip and strike directions, respectively. The angle β is the unknown angle between the dip direction and line 0-1. The angle of dip is denoted δ . The direction of dip relative to 0-1 and the dip angle are given by

$$\beta = \tan^{-1}\left(\frac{\sin \gamma_2 - \sin \gamma_1 \cos \theta}{\sin \gamma_1 \sin \theta}\right) \qquad \text{(B-16a)}$$

$$\delta = \sin^{-1}\left(\frac{\sin \gamma_1}{\cos \beta}\right) \qquad \text{(B-16b)}$$

where γ_1 and γ_2 are the apparent dip angles along lines 0-1 and 0-2, respectively. If β is close to 90 deg (i.e., line 0-1 is close to the strike), equation B-16b may not, as it stands, give an accurate value of δ. In that case, substitution of γ_2 for γ_1 and $\beta - \theta$ for β in equation B-16b will allow the dip angle to be computed by reference to line 0-2.

(11) In practice, this method of determining dip is infrequently used. If the dip angle is small (not exceeding 10 deg), it is sufficiently accurate for practical purposes to use the depths D_u and D_d as the vertical depths from the shot points to the interface. Also, dipping interfaces can conveniently be dealt with by the delay-time method, which may also be used for the interpretation of irregular or curved surfaces.

h. Delay Times. It has been pointed out that true refractor velocities cannot be determined by firing a shot at only one end of a seismic line, but that they can if arrival times are recorded from both ends. Using both forward and reversed lines, however, offers another significant advantage in that the true velocities and the thicknesses of layers can be computed on a much more detailed basis by means of delay times. Under favorable circumstances, depths can be determined beneath each geophone to allow mapping of irregular and dipping boundaries.

(1) Velocity determination. The velocity v_2 of an irregular or dipping refractor can be obtained, as shown in figure B-10, by plotting the difference between the arrival times t_{D1} and t_{D2}, for the forward and reversed shots, for each geophone against distance. It can be easily shown that the arrival time difference is given by

$$t_{D1} - t_{D2} = \frac{2x}{v_2} + \text{constant} \qquad \text{(B-17)}$$

It follows that differences in arrival times plotted against distance, x, will form a line, the reciprocal slope of which is half the velocity of the refractor. In figure B-10, arrival-time differences for a two-layer case have been plotted above and below an arbitrary reference line. The arrival times being differenced must represent arrivals from the same refractor. The method is frequently useful for determining whether the arrivals have been refracted from the same layer. A deviation of the points from a straight line may indicate either that there

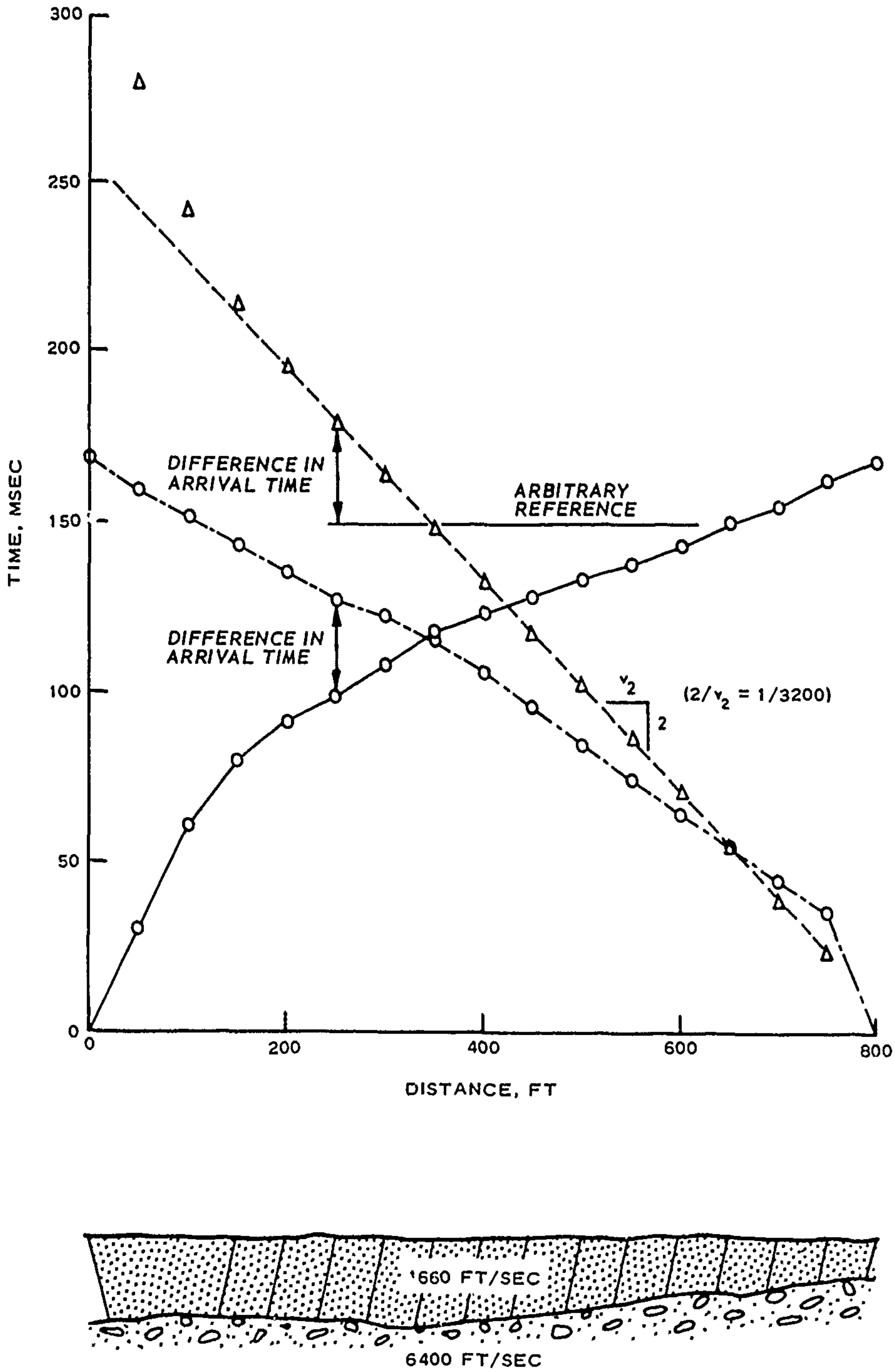


Figure B-10. True velocity of refractor from differences of arrival times (prepared by WES) exists a lateral variation of the refractor velocity, that the times being differenced represent arrivals refracted from different layers, or that the times represent both refracted and direct arrivals (note in figure B-10 the deviation of the points at 50 and 100 ft from the dashed line).

(2) Two-layer case.

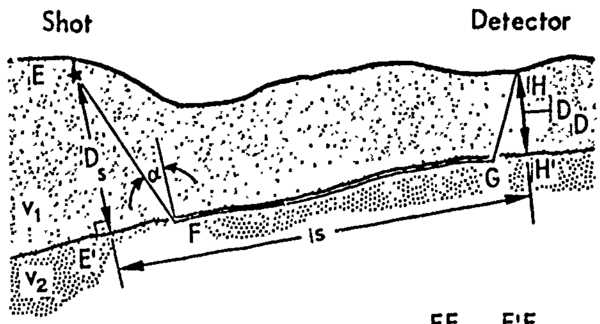
(a) The meaning of the term "delay time" is illustrated by figure B-11, in which the delay time is defined at the shot point and at the detector. The delay time is the difference between the actual travel time, over the refracted path through both layers, and the hypothetical time that would have been required, at the refractor velocity v_2, along the normal projection of this path on the interface. It is assumed that the interface is not highly irregular or steeply dipping, so that the distance along the interface between shot point and detector is approximately equal to the straight-line distance from shot to detector. The total delay time Δt is then given by

$$\Delta t = t_D - \frac{s}{v_2} \qquad \text{(B-18)}$$

where t_D is the arrival time at the detector. The total delay time consists of a delay time Δt_S at the shot point and a delay time Δt_D at the detector, so that

$$\Delta t = \Delta t_S + \Delta t_D \qquad \text{(B-19)}$$

For the pulse traveling up to the detector in figure B-11, the delay time has been defined as



$$\text{Delay time at shot point} = \Delta t_S = \frac{EF}{V_1} - \frac{E'F}{V_2}$$

$$\text{Delay time at detector} = \Delta t_D = \frac{GH}{V_1} - \frac{GH'}{V_2}$$

Figure B-11. Definition of delay time (after Redpath[20])

$$\Delta t_D = \frac{GH}{v_1} - \frac{GH'}{v_2} \tag{B-20}$$

This definition leads to the following relations between delay time and depth:

$$D_D = \frac{\Delta t_D v_1}{\cos\left(\sin^{-1}\frac{v_1}{v_2}\right)} \tag{B-21a}$$

or

$$D_D = \frac{\Delta t_D v_1 v_2}{\sqrt{v_2^2 - v_1^2}} \tag{B-21b}$$

Both forms are equivalent and may be used interchangeably. The same relations apply to the depth at the shot point, with the substitution of Δt_S and D_s. The depth D_D actually represents the depth of a point that is closer to the shot point (point G in fig. B-11), where the ray path is refracted at the interface between layers. The horizontal distance from the detector to this point, if the dip of the interface is small, is the distance GH', expressed as

$$GH' = D_D \tan \alpha \tag{B-22}$$

where α is the critical refraction angle (i.e., $\alpha = \text{arc sin } v_1/v_2$).

(b) In order to use equations B-21a and B-21b to find depths of a refractor, it is necessary to be able to separate the shot point and detector delay times from Δt. If one of the depths is known from boring data, the corresponding delay time can be computed from equations B-21a and B-21b and the rest of the delay times for the line can be obtained by applying equations B-18 and B-19. If no depths are known, the determination of delay times will require the use of a reversed seismic line, as shown in figure B-12, which shows the arrival times at the geophones from shots at both ends of a seismic line. The total travel time from one end of the line to the other (the "reciprocal" time) has been designated T_t and should be the same for both shots. The arrival times at one of the (arbitrarily selected) geophones from the two shots SP_1 and SP_2 have been designated t_{D1} and t_{D2}, respectively. If it is assumed that the distance along the refractor surface is nearly equal to the straight-line distance at the ground surface, and that the distances CD and ED (fig. B-12) are nearly equal, it can be shown that:

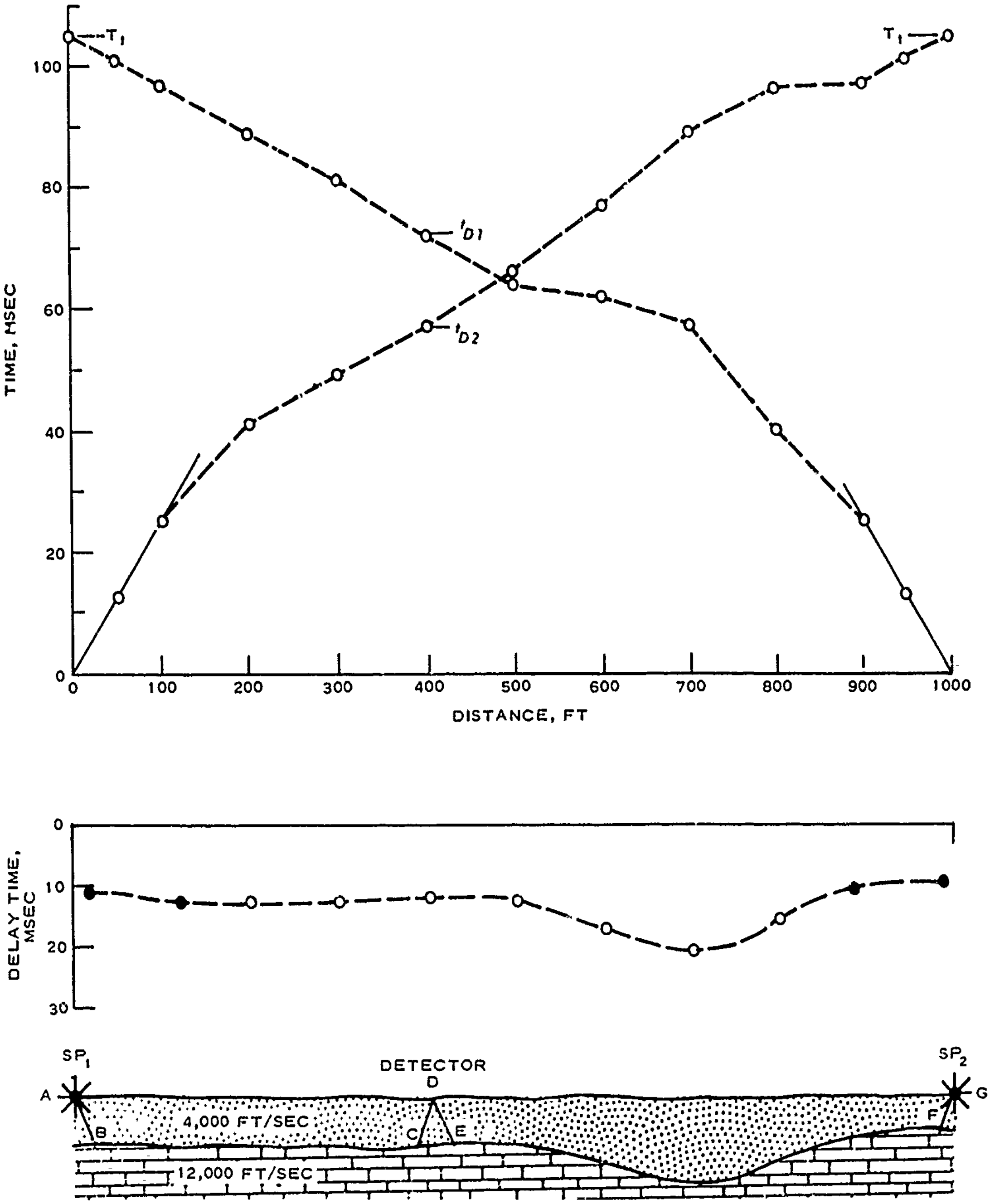


Figure B-12. Delay-time method of depth determination using reversed seismic line (prepared by WES)

$$\Delta t_D \cong \frac{1}{2} (t_{D1} + t_{D2} - T_t) \qquad \text{(B-23)}$$

where Δt_D is the delay time for the chosen geophone. This delay time is, in effect, an average for the forward and reversed lines. Therefore, Δt_D and the depth computed from it refer to the actual geophone location. It is important to note that T_t must represent the total time, or reciprocal time, for signals refracted at the same layer that is represented by the arrival times t_{D1} and t_{D2}. If the reciprocal time obtained represents some deeper layer, it is necessary to use one or more additional shot points on the line.

(c) As shown in figure B-12, a plot of delay time versus distance is similar to a profile of the refractor surface. The delay times shown with an open circle (fig. B-12) were obtained by using equation B-23. Those shown with a closed circle represent geophone locations at which a refracted first arrival was obtained in only one direction. Delay times were computed, therefore, from equations B-18 and B-19, after equation B-19 and a delay time for a geophone in the middle of the line were used to find the shot-point delay times. The delay times marked by closed circles are "migrated" toward their respective shot points, according to equation B-22.

(3) Multiple-layer case.

(a) The delay-time method can be extended to cases in which there are three or more layers, although three layers are usually the practical limit because of loss of accuracy and resolution as the number of layers increases. An important limitation is that the method can be applied only where there is "overlap" between arrivals refracted from the same layer. In other words, the actual length of the seismic line should be such that the forward and reverse arrival times at a geophone where delay time is to be computed represent signals refracted through the same layer. If a lack of overlap for deep refractors is noted in the field by reducing and plotting the data immediately after the shots, it is often possible to remedy the situation by firing additional shots off one or both ends of the line (i.e., beyond the ends of the geophone array) and in line with the array. It is also common in refraction investigations with long lines and multiple layers to have no overlap of refractions from the second layer. Resolution of this situation requires that some intermediate shots be fired along the length of the seismic line. The use of intermediate shot points is a good general practice. It will result in better control of first-layer depths and velocities and fewer assumptions are required to interpret the raw data.

(b) If the delay times in the first layer are subtracted from the corresponding arrival times and the differences plotted, the result is, in effect, a new time-distance curve that is equivalent to placing the shot and detectors at the top of the second layer. This plot of reduced arrival times can be interpreted in terms of delay times in the same manner as previously described. Some useful examples of the use of delay times are given by Redpath[20] and Black et al.[11]

i. Continuous Increase of Velocity with Depth. The case of velocity continuously increasing with depth is rare but may occur in such materials as hydraulic fill or dredge spoil. This type of situation can exist because of a finely stratified geology, a progressive decrease of weathering with depth, or a gradually increasing density with depth in soft soil resulting from consolidation under its own weight. A continuous increase of velocity with depth will produce a time-distance curve similar to the one shown in figure B-13. The ray paths are curved, and in the special case of a linear increase of velocity with depth, they are circular arcs.

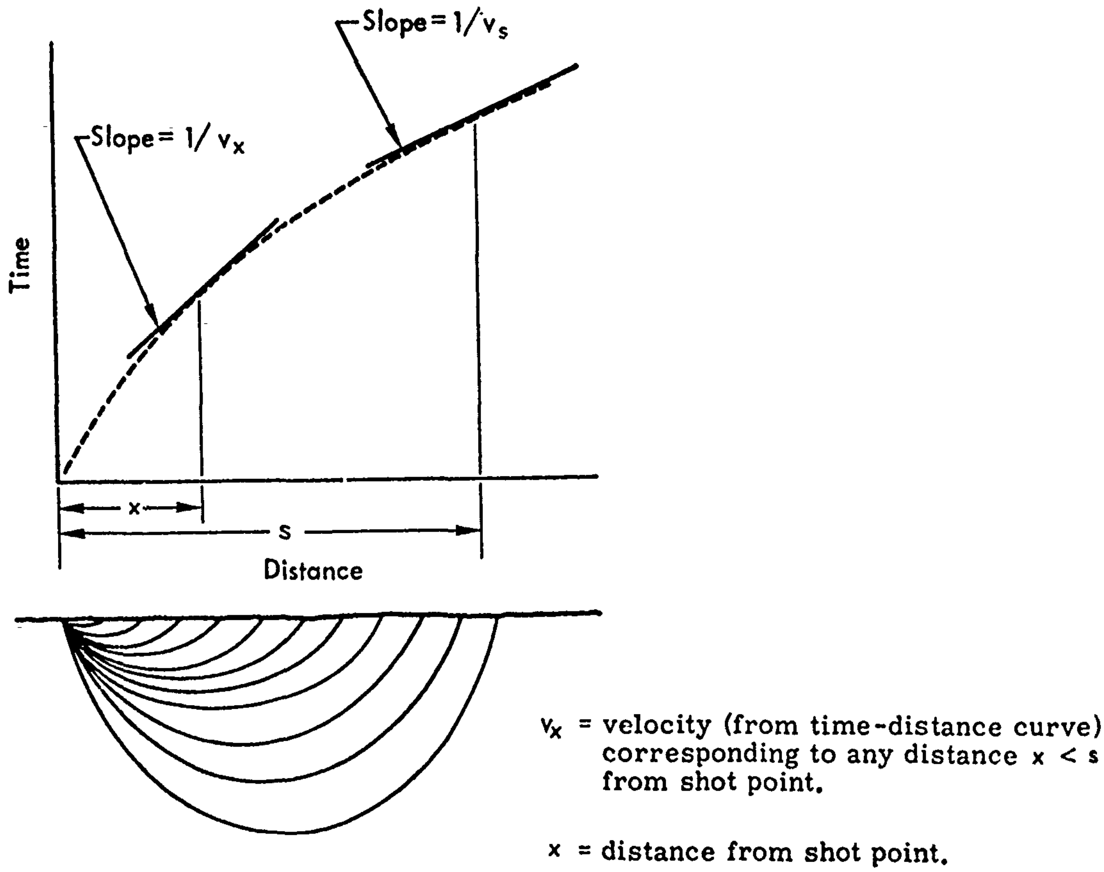


Figure B-13. Schematic of ray paths and time-distance curve for continuous increase of velocity with depth (after Redpath[20])

(1) This type of time-distance curve can be transformed into a curve of velocity versus depth by means of the "Herglotz-Weichert-Bateman" equation:[20,36]

$$D_s = \frac{1}{\pi} \int_0^s \cosh^{-1} \frac{v_s}{v_x}\, dx \qquad \text{(B-24)}$$

where

D_s = depth at which velocity is v_s
v_s = velocity (from time-distance curve) corresponding to distance s from shot point
v_x = velocity (from time-distance curve) corresponding to any distance $x < s$ from shot point
x = distance from shot point

The integral is evaluated graphically by choosing a particular distance s and the corresponding velocity v_s, obtained from the tangent to the time-distance curve at s, and plotting values of $\cosh^{-1}(v_s/v_x)$ against x, where x is any distance less than s. The area under the resulting curve (obtained numerically or with a planimeter) is multiplied by $1/\pi$ to determine the depth z_s at which the velocity is v_s. The integration is repeated for decreasing values of s, and the graph can then be constructed of the variation of velocity with depth. The method is tedious, although the integration can also be done numerically, with the aid of a digital computer, and it is justified only when there is a smooth, continuous increase of velocity with depth. Often, gradual increases of velocity can be interpreted by assuming that the curved time-distance plot is made up of a few straight-line segments. Interpretation can be aided in this case, also, by a digital computer, using equations B-10 and B-11. Any desired number of straight-line segments could be used. However, the largest number that could be meaningful would be one for each geophone, or each recorded arrival time.

(2) A special case of occasional interest is that of velocity increasing linearly with depth. The only situation that will be considered here is the one in which such a layer is at the ground surface. The velocity for this case is given by

$$v = v_o + kz \qquad \text{(B-25)}$$

where

v = velocity at depth z
v_o = velocity at ground surface
k = rate of velocity increase

It has been determined that the ray path in such a medium is a circular arc with a center at a distance v_o/k above the surface. According to Dobrin,[36] the lowest point on the path is at a depth

$$D_{max} = \frac{v_o}{k}\left\{\left[1 + \left(\frac{kx}{2v_o}\right)^2\right]^{1/2} - 1\right\} \tag{B-26}$$

and the travel time t for this path is given by

$$t = \frac{2}{k}\sinh^{-1}\frac{kx}{2v_o} \tag{B-27}$$

Moreover, the velocity at depth D_{max} is equal to the reciprocal of the slope of the time-distance curve at distance x.

(3) The parameters v_o and k can be obtained from the time-distance plot and equation B-27. Any two distances, x_1 and x_2, and the corresponding times, t_1 and t_2, can be chosen from the part of the time-distance plot corresponding to the surface layer. Two simultaneous equations can then be written

$$t_1 = \frac{2}{k}\sinh^{-1}\frac{kx_1}{2v_o} \tag{B-28a}$$

$$t_2 = \frac{2}{k}\sinh^{-1}\frac{kx_2}{2v_o} \tag{B-28b}$$

and solved by trial to obtain v_o and k. A convenient way to do this is to write equation B-27 in the form

$$v_o = \frac{kx}{2\sinh\frac{kt}{2}} \tag{B-29}$$

and to plot a curve of v_o versus k for one set of time and distance values. This is repeated for a second time and distance, and the intersection of the two curves will give the required values of v_o and k. While v_o and k can be determined from only two pairs of time and distance values, the exercise should be repeated with several sets of values in order to obtain the best average and to determine how well the data fit the assumed model.

(4) If a surface layer with a linear increase of velocity is underlain by a layer with a velocity v_2, higher than any in the surface layer, the time-distance plot will have a straight-line segment with a slope equal to $1/v_2$. The time intercept T_i for this line segment can be obtained by projecting it back to the time axis in the same manner as previously described. The relation between the thickness D_1 of the surface layer and T_i is given by:

$$T_i = \frac{2}{k}\left[\cosh^{-1}\frac{v_2}{v_o} - \cosh^{-1}\frac{v_2}{v_o + kD_1} - \sqrt{1 - \left(\frac{v_o}{v_2}\right)^2} + \sqrt{1 - \left(\frac{v_o + kD_1}{v_2}\right)^2}\right] \tag{B-30}$$

The velocity v_2 and the parameters v_o and k are obtained as described above. The thickness D_1 can only be determined by trial, since equation B-30 cannot be solved explicitly for D_1.

j. <u>Correction for Shot Depth and Elevation Differences</u>.

(1) In all of the foregoing discussions, it was assumed that the shot was placed at the ground surface and that the ground surface, or at least the positions of the geophones, could reasonably be represented as a plane. The ground surface was not necessarily required to be horizontal but was taken as a reference plane; all positions and dips of subsurface boundaries were thus determined with respect to that reference plane. In practice, the shot is frequently placed at a depth of several feet in a borehole, and the ground surface may have enough irregularity to produce significant errors if calculations are made as though it were a plane. Also, it may be desirable to refer the data to a horizontal reference.

(2) The elevation and shot depth corrections may be treated together, as shown in figure B-14. The shot and detector are reduced to a common datum by adding or subtracting a delay time corresponding to the elevation difference. The elevation correction, which is to be <u>subtracted</u> from the arrival time value, is

$$\text{Elevation correction} = \frac{(e - h + E - 2d)\sqrt{v_2^2 - v_1^2}}{v_1 v_2} \tag{B-31}$$

where

e = elevation of ground surface at shot point above sea level
h = depth of shot below ground surface
E = elevation of geophone above sea level
d = elevation of datum plane above sea level

All depths and thicknesses are then obtained with respect to the datum plane. Frequently it is sufficient to correct only for the depth of the shot. In this case, a very good approximation is obtained by the following rule: Add one half of the shot depth to the apparent thickness of the surface layer as computed from formulas based on the surface shots.

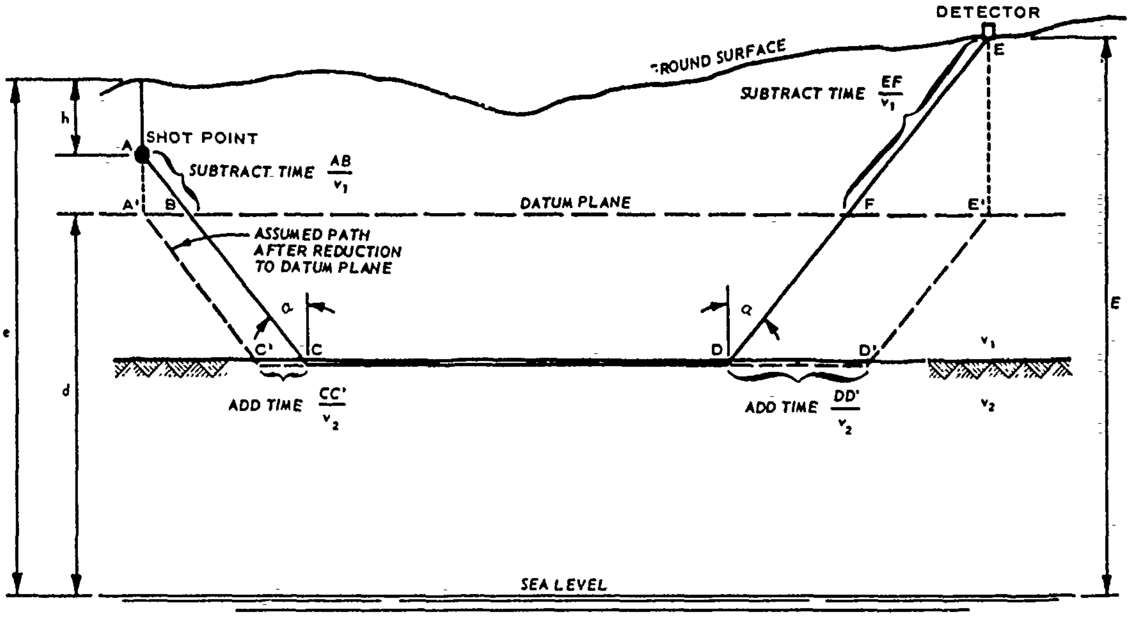


Figure B-14. Elevation correction for the two-layer case; d is the elevation of the datum plane, e the elevation of the ground at the shot point, E the elevation of the detector, and h the depth of the shot below the ground surface (after Dobrin[36])

k. Examples of Time-Distance Plots. In the following paragraphs, examples are given of some normal and problem conditions and the time-distance plots that would be encountered.

(1) Buried shot. If the shot is buried, the arrival time t_o at the ground surface over the shot point is equal to h/v_1, where h is

the shot depth. The theoretical time-distance plot for the surface layer would be a hyperbola, with a time-intercept t_o, asymptotic to the line with slope $1/v_1$, as shown in figure B-15. In most actual field cases, the geophone spacing would not be close enough to define the hyperbola well, but the time intercept may be apparent.

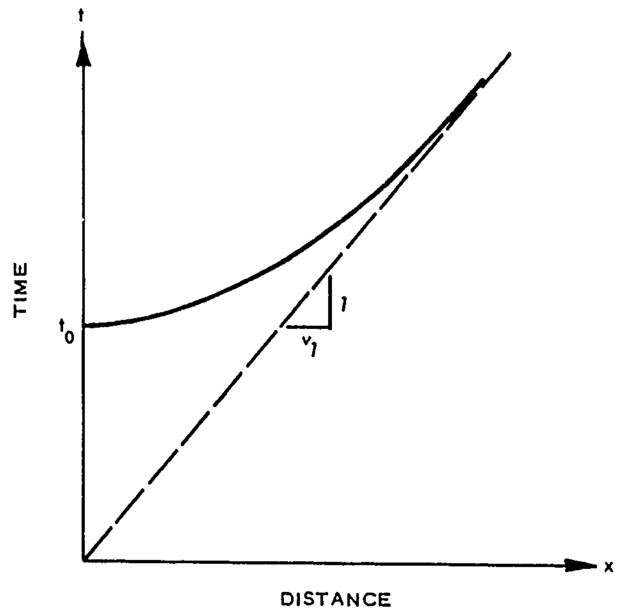
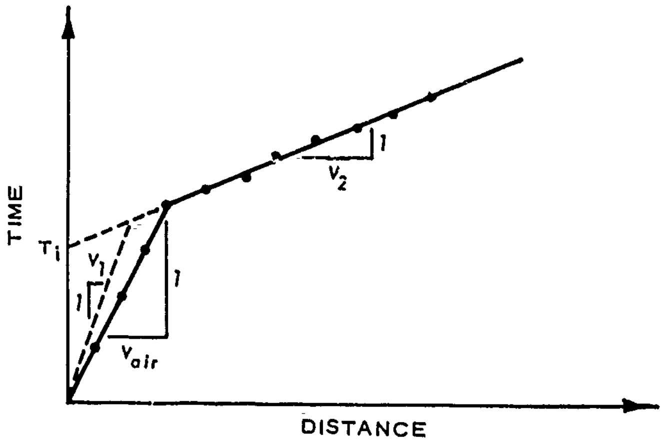


Figure B-15. Effect of burial of shot on initial portion of time-distance plot (prepared by WES)

(2) Soil of low velocity. Occasionally soils are encountered with P-wave velocities of a few hundred feet per second. Such a velocity is less than the velocity in air, which is 1127 ft/sec under standard conditions. If the shot is at the surface, the first segment of the time-distance plot will indicate a velocity of about 1100 ft/sec, because the first-arriving signal will be one that is propagated through the air (fig. B-16). While apparent velocities of deeper refractors will not be affected, the depths to these deeper layers will be incorrectly computed because the surface layer velocity is erroneously taken to be 1100 ft/sec. The true velocity of the surface layer can be obtained by using a buried shot and computing the velocity from the arrival times and slope distances from the shot to nearby geophones. The depth of the surface layer can be computed from the time intercept and the true velocities. Note that the use of the critical distance



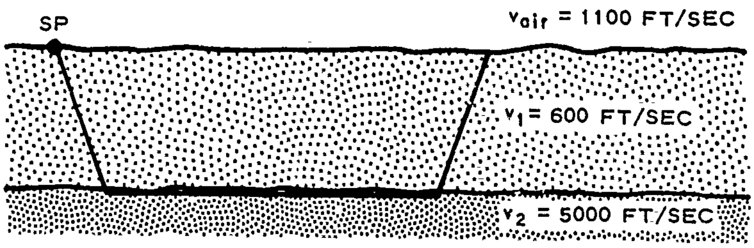


Figure B-16. Time versus distance plot for surface layer with velocity less than air (prepared by WES)

method would give an erroneous depth in this case. Wherever an apparent surface layer velocity of about 1100 ft/sec is encountered, the possibility that air waves are being observed should be considered. This condition can sometimes be detected by the shape of the recorded wave forms. If the geophones are vertically oriented, an air-wave arrival may produce a first break in the direction opposite to that given by a signal transmitted through the soil.

(3) Groundwater table. The compression wave velocity of water is about 4800 ft/sec, and the velocity of loose, saturated soil is usually in the vicinity of 5000 ft/sec. Therefore, a horizontal interface with a velocity of about 5000 ft/sec below it is frequently indicative of a groundwater table. This can sometimes be determined by observation of the slower shear waves. Since the propagation velocity of shear waves is nearly independent of water content, there is no change in shear wave velocity at the water table, and no refraction of the shear wave.

(4) High or low points on rock surface. Abnormally high or low points in the buried rock surface may plot below the average velocity line, where there is a rise in the rock profile, or above the velocity line where a large depression exists, as shown in figure B-17. Also, points will plot above or below the line where an uneven ground surface lies over a smooth rock surface, unless an elevation correction is applied.

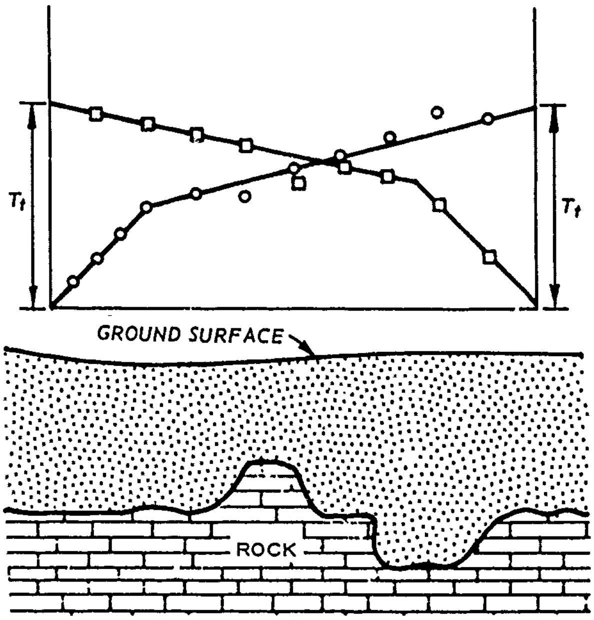


Figure B-17. High or low points on rock surface (prepared by WES)

(5) Change in dip. A change in dip of the refractor surface along the line of the seismic profile is illustrated in figure B-18. The change in dip is indicated by a change in slope of the time-distance plot. Such a curve could also be produced by a change in slope of the ground surface, if elevation corrections are not applied.

(6) Buried rock ledge. Beyond the end of a buried rock ledge, the upward turn of the time-distance curve, as shown in figure B-19, indicates that low-velocity materials exist beyond the end of the ledge.

(7) Subsurface stream channel. A subsurface deeply incised stream channel or cliff will give unusual velocity curves, as illustrated in figure B-20. The sloping edge of the channel is indicated by a reduced apparent velocity on the shot in the downslope direction and an increased apparent velocity in the opposite direction. This kind of

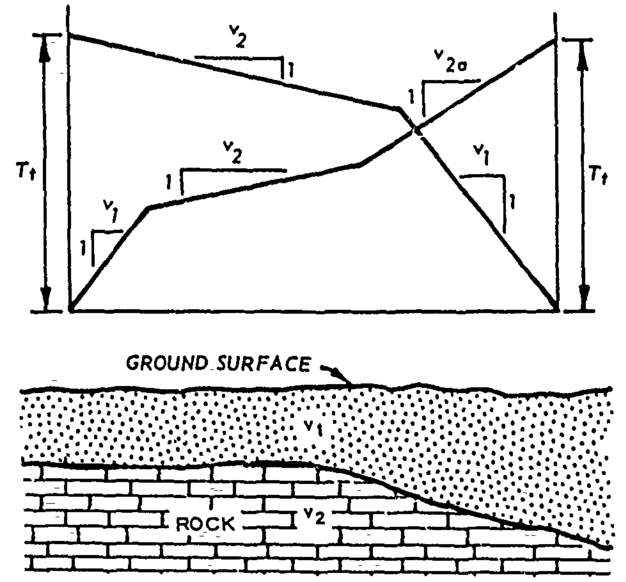


Figure B-18. Change in dip of refractor surface (prepared by WES)

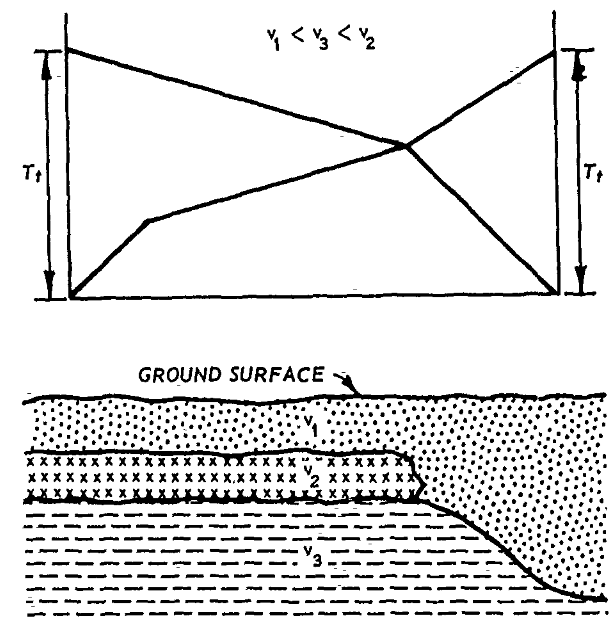


Figure B-19. Buried rock ledge (prepared by WES)

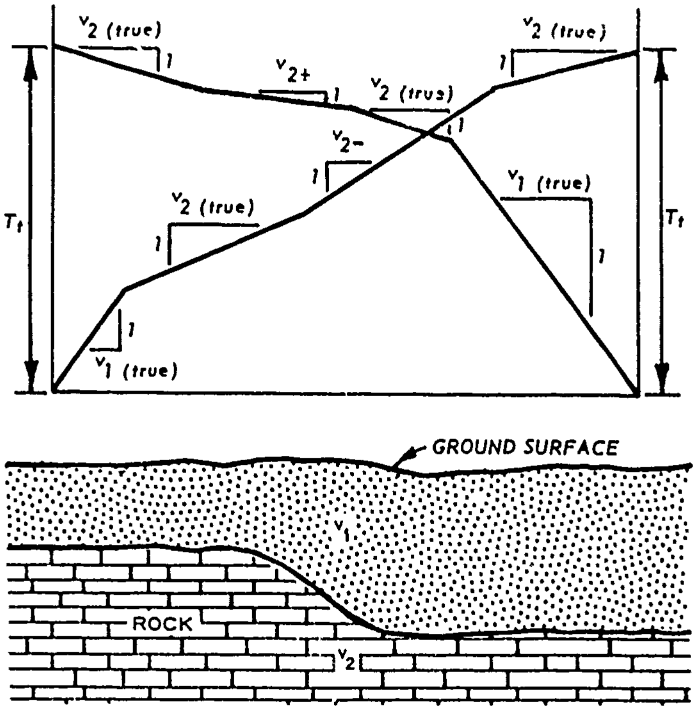


Figure B-20. Subsurface stream channel
(prepared by WES)

condition can usually be resolved by the use of delay times, except in the vicinity of very steep or irregular surfaces.

(8) Subsurface cliff. For this case, the time-distance plot in figure B-21 is somewhat similar to that in figure B-20. However, the slope of the break of the rock surface is very steep, and there is a definite up-or-down offset in the time-distance curve.

(9) Offset in time-distance curve. An offset in the time-distance curve can be caused by any one of several conditions. Among the possibilities are: (a) erroneously plotting arrivals due to vibration cycles later than the first arrival, usually because of weak first arrivals or excessive background noise; (b) a vertical offset in the refractor surface, as shown in figure B-21; and (c) the presence of a fractured fault zone, vertical mud seam, open cavern, sinkhole, or grike across the seismic line. In case (b), the sense of the offset is reversed when the direction of the shot is reversed (fig. B-21), while in case (c) the offset is positive for both directions (fig. B-22).

(10) Subsurface fault. A forward and reverse spread across steeply dipping or faulted massive bedrock overlain by alluvium would

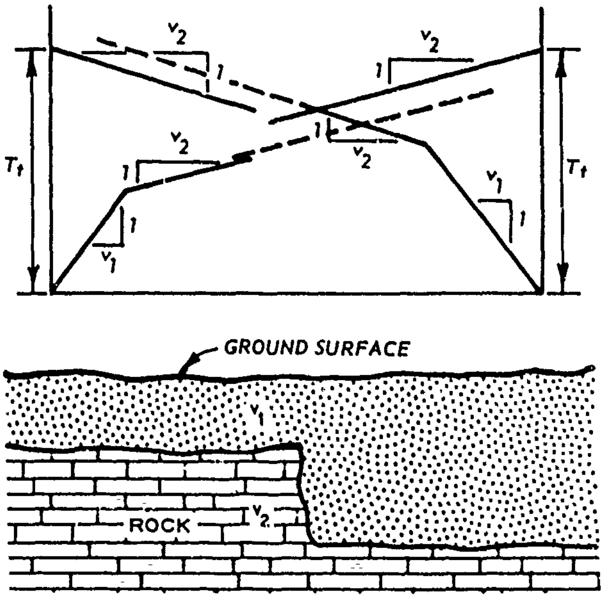


Figure B-21. Subsurface cliff
(prepared by WES)

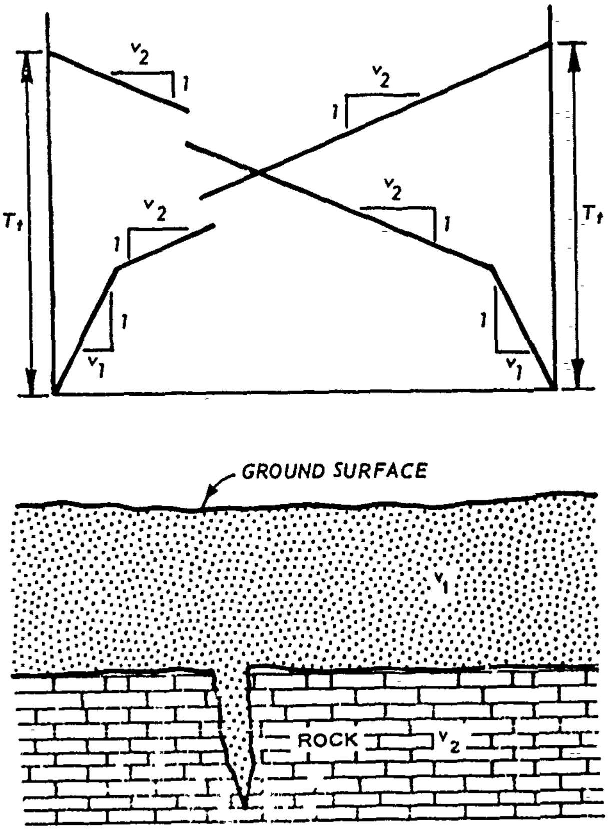


Figure B-22. Offset in time-distance plot due to discontinuity in rock surface
(prepared by WES)

yield time-distance curves similar to those shown in figure B-23. The apparent velocities v_1, v_2, and v_3 are true velocities.

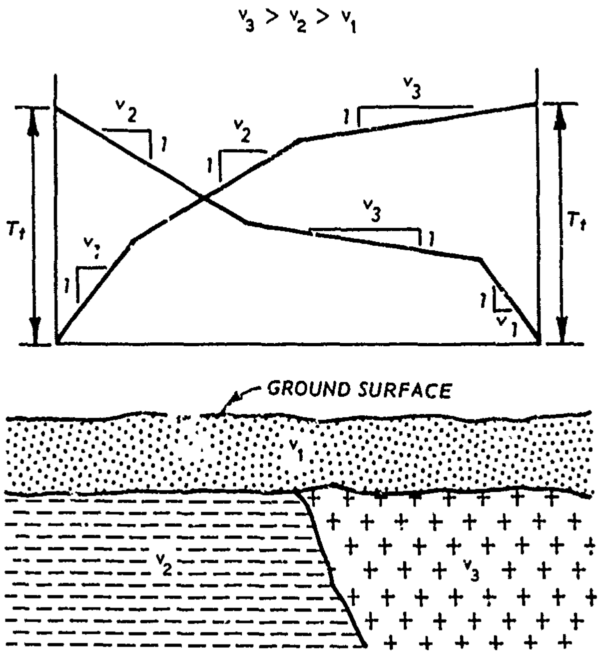


Figure B-23. Subsurface fault
(prepared by WES)

(11) Buried ridge. A vertical or steeply dipping buried ridge of high-velocity rock aligned at an angle to the direction of the survey line may give a time-distance plot similar to that shown in figure B-24. Unless an outcrop is found that will provide an indication of thickness and direction of strike, several survey lines may be required to define the feature.

l. Typical Velocities of Geologic Materials. Table B-1, reproduced from superseded EM 1110-2-1804, lists typical longitudinal, or compression, wave velocities of various soil and rock materials. They are presented here to give some idea of what velocities mean in terms of geologic media.

B-5. Limitations, Accuracy, and Resolution.

a. General. A fundamental limitation in the seismic refraction method lies in the fact that a given set of arrival time and distance data cannot be associated with a unique set of subsurface conditions. In principle, for a given system of velocity distribution in the

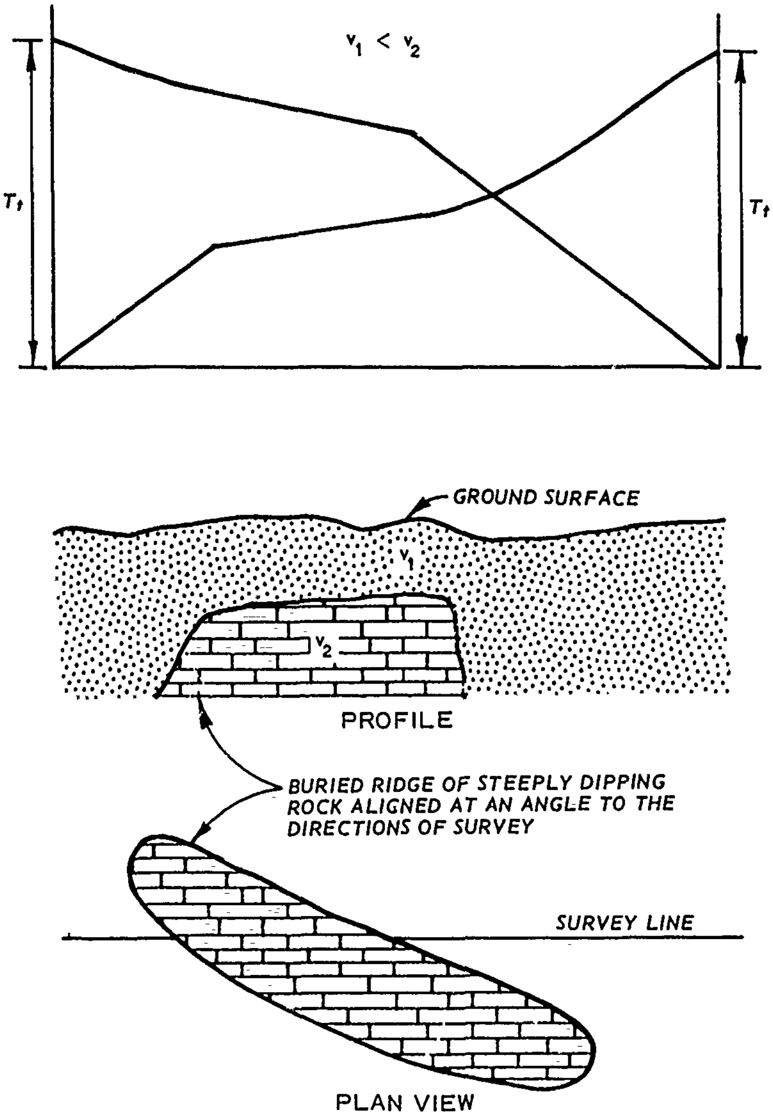


Figure B-24. Buried ridge (prepared by WES)

subsurface, it is always possible to synthesize a one-and-only time versus distance plot, no matter how much the subsurface conditions are complicated by faults, peculiar boundary shapes, or unusual distributions of velocity with depth. However, the problem met with in seismic exploration is the inverse--that of proceeding from time-distance plots to evaluation of subsurface conditions--and uniqueness of the solution is not assured. Ambiguity can often be reduced by additional shooting with some part of the layout changed; a simple example of this is the use of reversed lines to distinguish between horizontal and dipping

Table B-1. Velocity of Propagation of Seismic Waves in Subsurface Materials[a]

Materials	Feet per Second
Top Soils:	
Light and dry	600 to 900
Moist, loamy or silty	1,000 to 1,300
Clayey	1,300 to 2,000
Red clay in Colorado (A)	1,630
Semi-consolidated sandy clay (B)	1,250 to 2,150
Wet loam (B)	2,500
Clay, dense and wet - depending on depth	3,000 to 5,900
Rubble, or gravel (B)	1,970 to 2,600
Cemented sand (B)	2,800 to 3,200
Sand clay (B)	3,200 to 3,800
Cemented sand clay (B)	3,800 to 4,200
Water saturated sand (B)	4,600
Sand (B)	4,600 to 8,400
Clay, clayey sandstone (B)	5,900
Glacial till Upper Susquehanna (C)	5,600 to 7,400
Glacial moraine deposit, dry-California (A)	2,500 to 5,000
Glacial moraine deposit, saturated-California	5,000 to 7,000
Cemented lava agglomerate, California (A)	5,000 to 6,000
Loose rock-talus	1,250 to 2,500
Weathered and fractured rock	1,500 to 10,000
Shale:	
Olentangy River, Ohio	9,000 to 11,000
Upper Susquehanna (C)	10,200 to 12,800
Panama Canal Zone	7,000 to 8,000
Mancos, Colorado (A)	2,600 to 2,900
Romney Shale-Shennandoah River - weathered	4,000 to 6,500
Romney Shale-Shennandoah River - good	12,000
John Marshall Dam Site	2,900 to 4,250
Phyllite-York, Pa. (D)	10,000 to 11,000
Sandstone: (B)	7,200 to 7,900
Devonian-Upper Susquehanna (C)	14,000
Canal Zone, Pacific end	7,000 to 9,000
Colorado, dense, hard, and continuous with few seams (A)	7,250
Colorado, containing weathered seams and soft areas. (A)	4,725
Smoky Hill River, Kansas	6,000 to 7,500
Sandstone conglomerate (B)	8,000
Chalk:	
Fort Randall Damsite - Above water table	6,300 to 7,000
Fort Randall Damsite - Below water table	8,000

Materials	Feet per Second
Granite:	
Sierra Nevada Range, California (in road cuts)	
Friable and highly decomposed	1,540
Badly fractured and partly decomposed	2,200
Softened and partly decomposed but slightly seamed	10,500
Solid and monolithic 70 feet deep	18,500
New Hampshire (C) (Comparison of velocities with drilling logs)	
Badly broken and weathered; frequently only chips and fragments recovered. Segments of core longer, but weathering had penetrated about 1/4 inch on each side of the joint planes on which a film of residual clay had formed	3,000 to 8,000
Joint planes show but little sign of weathering, even though they are open	10,000 to 13,000
Entirely unweathered and unseamed	16,000 to 20,000
Granodiorite (B)	15,000
Basalt-Canal Zone-weathered and fractured	9,000 to 14,000
Limestone, dolomite, metamorphic rocks, massive rocks (B)	16,400 to 20,200
Diabase, in bed of Broad River, South Carolina	19,700
Greenstone, tight seamed-California (A)	16,100
Greenstone, slightly seamed-California	13,300

NOTE:

(A) *Reported by G. H. Williams, U. S. Bureau of Public Roads*

(B) *From Report of Imperial Geophysical Experimental Survey in Australia*

(C) *Reported by A. E. Wood, Corps of Engineers*

(D) *Reported by L. T. Abele, Corps of Engineers*

a Prepared by WES from information given in superseded EM 1110-2-1802 dated September 1948.

interfaces. In some other situations, surface shoc' ' 'g alone, no matter how it is arranged, cannot resolve all ambiguities . some direct information, such as borin data, is required. Because of this inherent limitation in the seismic method, a seismic survey alone can never be considered definitive. Properly integrated with other complementary explorations methods, however, seismic fraction surveying is a highly effective, accurate, and cost-effective method of obtaining subsurface information. In the following paragraphs, some specific limitations and sources of error are discussed.

b. Velocity Reversals.

(1) Throughout the preceding discussions, it has been explicitly assumed that the velocities of the soil or rock layers increase with depth. If in the field a layer is encountered with material of higher velocity above it, the low-velocity layer cannot be detected surface refraction surveys, and the computed depths of deeper layers will be too great. Although the most common condition is that of velocity increasing with depth, there are many kinds of situations in which velocity reversals can occur. Examples can be found in the cases of sands overlying organic bog soils, glacial till overlying lacustrine sediments, or basalt flows in alluvial sediments.

(2) Figure B-25 illustrates a hypothetical four-layer case in which layer 2 has a lower velocity than the surface layer. The ray path is shown for a first arrival that is refracted through layer 4. The path is governed by Snell's law, as always, and the ray is refracted toward the normal in layer 2. There is no possible ray path representing a first arrival with its deepest part in layer 2; so there is no indication of layer 2 in the time-distance plot. The time-distance plot, in fact, is indistinguishable from that of a three-layer system with velocity increasing downward.

(3) The effect of a low-velocity layer is to make the computed depths greater than actual depths. This is due to the fact that the time required for the signal to traverse layers 1 and 2 is greater than it would be if v_2 were equal to v_1, while the depths are computed as though the whole distance from the surface to layer 3 were traversed at v_1, the higher velocity. If the presence and velocity of a low-velocity layer are known, the layer can be compensated for in the computations, but its existence must be determined by means of a more direct method, such as an uphole velocity survey.

c. Blind Zones.

(1) A blind zone, or hidden layer, is a layer that cannot be

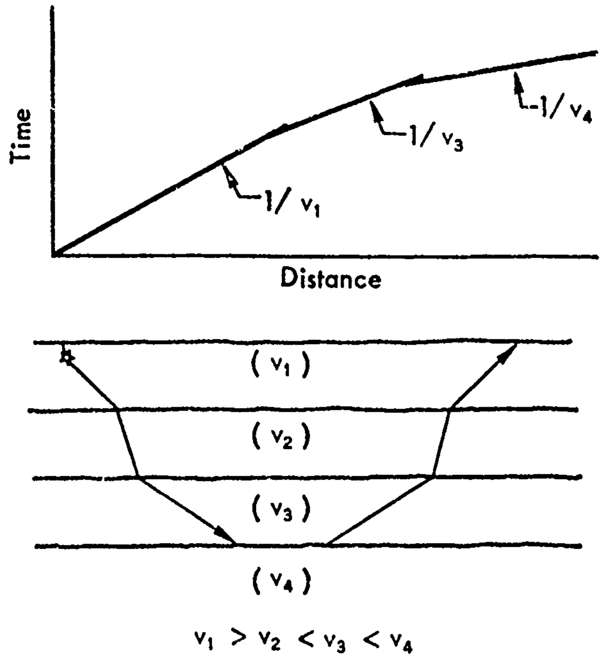


Figure B-25. Velocity reversal and corresponding time-distance curve (after Redpath[20])

detected by the refraction seismograph because of insufficient velocity contrast or thickness. This inability cannot be remedied by any change in the layout of the geophones, but only by applying information from borings. In most cases, the blind zone will lie between the surface and a high-velocity layer.

(2) An example of this type of problem is given by Soske.[71] Figure B-26 depicts an example of a three-layer case with the layers having good velocity contrasts. In the wave-front diagram, note that the head wave from the high-velocity layer 3 overtakes the head wave from layer 2 at some distance from the shot. If layer 2 is thin, that distance may be less than the critical distance of layer 2. The example in figure B-26 shows the case where the overtaking distance is just equal to the critical distance of the intermediate, 8500-ft/sec layer. Thus, it shows the minimum thickness of the intermediate layer that would have to exist before its presence could be detected by first arrivals, regardless of the geophone layout. However, there is no indication of the 8500-ft/sec layer on the time-distance curve; it would be necessary that the layer in figure B-26 be at least 70 ft thick in order that refractions from it be recorded as first arrivals.

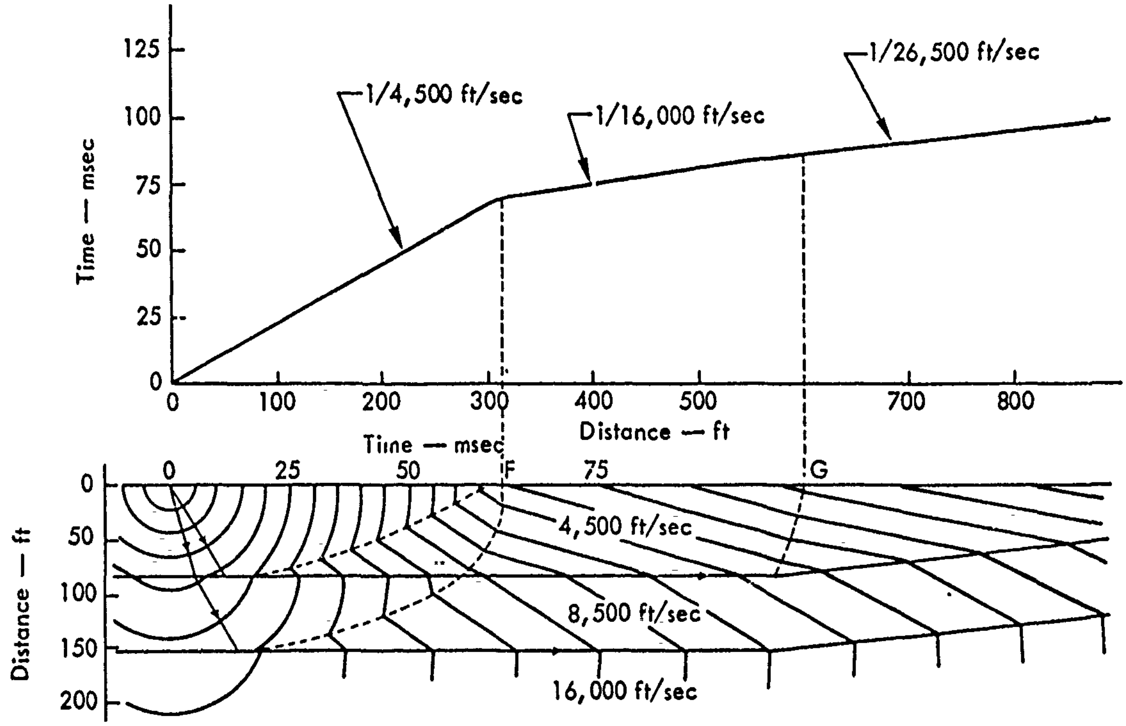
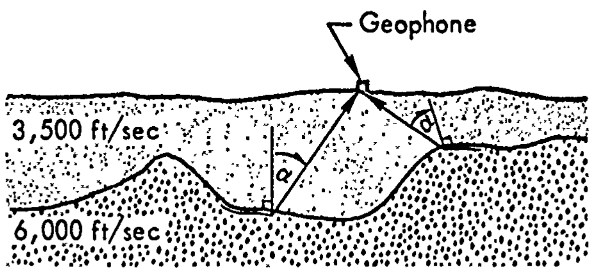


Figure B-26. Wave-front diagram and maximum undetectable thickness of blind zone (courtesy of Society of Exploration Geophysicists[71])



$$\alpha = \sin^{-1} \frac{3,500}{6,000} = 35.7°$$

Figure B-27. Schematic of shallow, irregular refractor surface producing different first-layer travel times at same geophone from shots on either side of it (from Redpath[20])

(3) The problem can be overcome by firing a shot in a deep hole so that arrivals from the intermediate layer are recorded at the surface. Of course, it would be necessary that the existence of the intermediate layer be known beforehand because of some other source of information, such as a drill hole, before this would normally be attempted. If a time-distance curve shows a very large velocity contrast between the first and second layers, the existence of a blind zone might be suspected. The error that results from not knowing the existence of a blind zone is that the computed depth to the refracting layer is too shallow. However, even in the worst case, it is doubtful whether the error would approach 50 percent. A nomograph that can be used to determine the maximum possible thickness of blind zones is given by Redpath.[20]

(4) The hidden layer problem can be a serious drawback to shallow surveys with the refraction seismograph. The possibility of such a layer's existence emphasizes the desirability of using an exploratory drill hole in conjunction with seismic surveys whenever possible.

d. Accuracy and Resolution.

(1) Generally, as the depth of the investigation becomes shallower, the resolution limits of the method are approached, and the inherent uncertainties become more important. A large proportion of refraction surveys for engineering purposes are concerned with depths of 50 to 75 ft and total times of 50 to 100 msec. It is apparent then that a millisecond is a large unit of time, and arrival times must be picked with an accuracy of a millisecond or less. This means that the charge weight, its surrounding medium and coupling, the amplifier gains, and the placement of the geophones are all important factors in obtaining the sharp breaks required for accurate timing of first arrivals. An error of 1 msec corresponds to only 1 ft of depth with a first-layer velocity of 2,000 ft/sec, but the error would be 5 ft for a first-layer material with a velocity of 10,000 ft/sec.

(2) Generally, in working with short lines of 500 ft or less, obtaining sharp breaks will not be a problem, unless there is difficulty in burying sufficient explosive deep enough. Because of the attenuation of the explosive impulse with increasing distance, and particularly because of the relatively greater attenuation of the high-frequency components, the arrivals tend to become less distinct and more rounded with increasing distance from the shot. The objective is to pick arrival times to within 1 msec or less, using what appears to be the onset of the pulse. The presence of background noise, such as that generated by vehicle traffic, or weak arrivals caused by poor charge coupling, can

make accurate determinations difficult.

(3) The effect of a 1-ft error in the surveyed elevation of a shot point or geophone is the same as a 1-msec error in timing for a 2000-ft/sec material. Any effort spent in obtaining arrival times to a higher degree of precision would be wasted if surveying errors of this magnitude existed. The needed degree of precision varies with the nature of the project for which the survey is made, so no general rule can be stated. However, the precision needed for a survey should be considered in planning the fieldwork, and all measurements should be performed with equivalent degrees of refinement.

(4) It is necessary to maintain close control of overburden velocities and depths, particularly to distinguish travel time spent in the overburden from time spent in underlying, higher velocity layers. This is particularly so when there are more than two layers. Unconsolidated overburden deposits frequently show lateral changes in velocity over relatively short distances, and it is almost always desirable to fire at least one intermediate shot between the ends of the line.

(5) Irregularities in a shallow bedrock surface have a more pronounced effect on accuracy than irregularities in a deeper horizon. A highly irregular refractor surface will tend to make delay-time methods somewhat inaccurate because the times being compared represent different depths, depending on the direction of the shot. This situation is depicted in figure B-27. The effect of using delay times to compute depths will be to "smooth" a highly irregular surface. The situation is aggravated if the velocity contrasts are not large, i.e., if the horizontal offsets between the geophone and the point at which the ray emerges from the refractor ($\approx Z \tan \alpha$) are large.

(6) Further complications arise if the rock surface is not only eroded and irregular but also weathered. In this case, the rock surface may not be a well-defined boundary but rather a zone of transition. In the case of layered rock, some of the layers may be better media for the transmission of seismic energy, and the refractions may not necessarily be from the top of the rock. Also, as distance from the shot increases, the higher frequency (i.e. shorter wavelength) energy is progressively absorbed; because of the signal's increasing wavelength, the energy may refract from progressively thicker beds. It is necessary to bear in mind that the wavelength becomes a significant factor when the refractor is of a limited thickness. Long-wavelength seismic signals do not "see" thin beds.

(7) Some materials may be anisotropic, i.e., there may be differences between horizontal and vertical velocities, or even between

horizontal velocities in different directions. These differences may be as large as 40 percent in some materials. Rocks with finely bedded structure, such as sandstones and shales, generally exhibit some degree of anisotropy.

APPENDIX C

EXAMPLES TO ILLUSTRATE THE USE OF SEISMO

Examples to Illustrate the Use of Seismo

1. This appendix contains three examples of cases where seismo was used for data reduction and presentation. Each case was chosen to present and explain a certain aspect of the programs data reduction capabilities. Example one (Figures 1-4) gives a case where a forward traverse only was done (shotpoint on one end of the spread only), this case is presented to explain how seismo handles a single sided traverse. Example two (Figures 5-12) gives a case where a forward and reverse traverse were performed (shotpoint on both ends of the line). This case also presents the use of a shorter line on one or both ends (overburden line) to serve as a more precise measurement of the near surface layering. This case is repeated with the units changed from feet to meters. Example three (Figures 13-17) presents a case in which the terrain correction routine was utilized to correct the data for elevation changes.

2. Example 1. The case presented as example 1 is shown in Figures 1 through 4. Figure 1 is a printout of the data reduced from information collected in the field. For this particular case, there were twelve geophones in the spread. A shotpoint was placed on one end of the line only, referred to as the forward traverse. Notice that the printout indicates zero reverse points beside the heading REVERSE POINTS. The data is located in a file named KWAJ1.REF, and has the identifier kwaj1. The total line length from shotpoint to last geophone is 42 ft, the geophones are spaced 2 ft apart, and the shotpoint to first geophone distance is 2 ft. The file also contains a model that was saved with the data, and is shown at the bottom of the figure. This model information is input only, meaning that the results, layer velocities and depths to interfaces, would have to be calculated through the program using the invMOD and Calculate options.

3. A plot of the data from example 1 is shown in Figure 2. This is the working plot, 5x7 inches, used to present the data on a large scale to aid in determination of the layering. The plot also contains a working model represented by the solid lines running through the data. Notice that there is a reverse model, even though there is no reverse data (no shotpoint at the far end). This illustrates the method seismo uses to calculate the results. If only a forward model exist (or alternately a reverse model only) the program will make the reverse model equal to the forward model because both are necessary to calculate the

SEISMIC DATA SUMMARY

DATA FILE NAME : a:KWAJ1.REF
DATA IDENTIFICATION : kwaj1
THERE ARE : 12 FORWARD POINTS 0 REVERSE POINTS
LINE LENGTH : 42 ft

*** FORWARD POINTS ***		*** REVERSE POINTS ***	
Distance ft	Time msec	Distance ft	Time msec
2.0	1.2	0.0	0.0
4.0	2.9	0.0	0.0
6.0	4.1	0.0	0.0
8.0	5.5	0.0	0.0
10.0	6.5	0.0	0.0
12.0	7.9	0.0	0.0
17.0	11.0	0.0	0.0
22.0	12.5	0.0	0.0
27.0	13.6	0.0	0.0
32.0	14.2	0.0	0.0
37.0	15.2	0.0	0.0
42.0	16.2	0.0	0.0

END OF DATA

MODEL SAVED WITH DATA

*** FORWARD MODEL ***		*** REVERSE MODEL ***	
Velocity ft/sec	Intercept msec	Velocity ft/sec	Intercept msec
1543	0.0	1543	0.0
4721	7.5	4721	7.5

Figure 1. Printout of time-distance data for example 1.

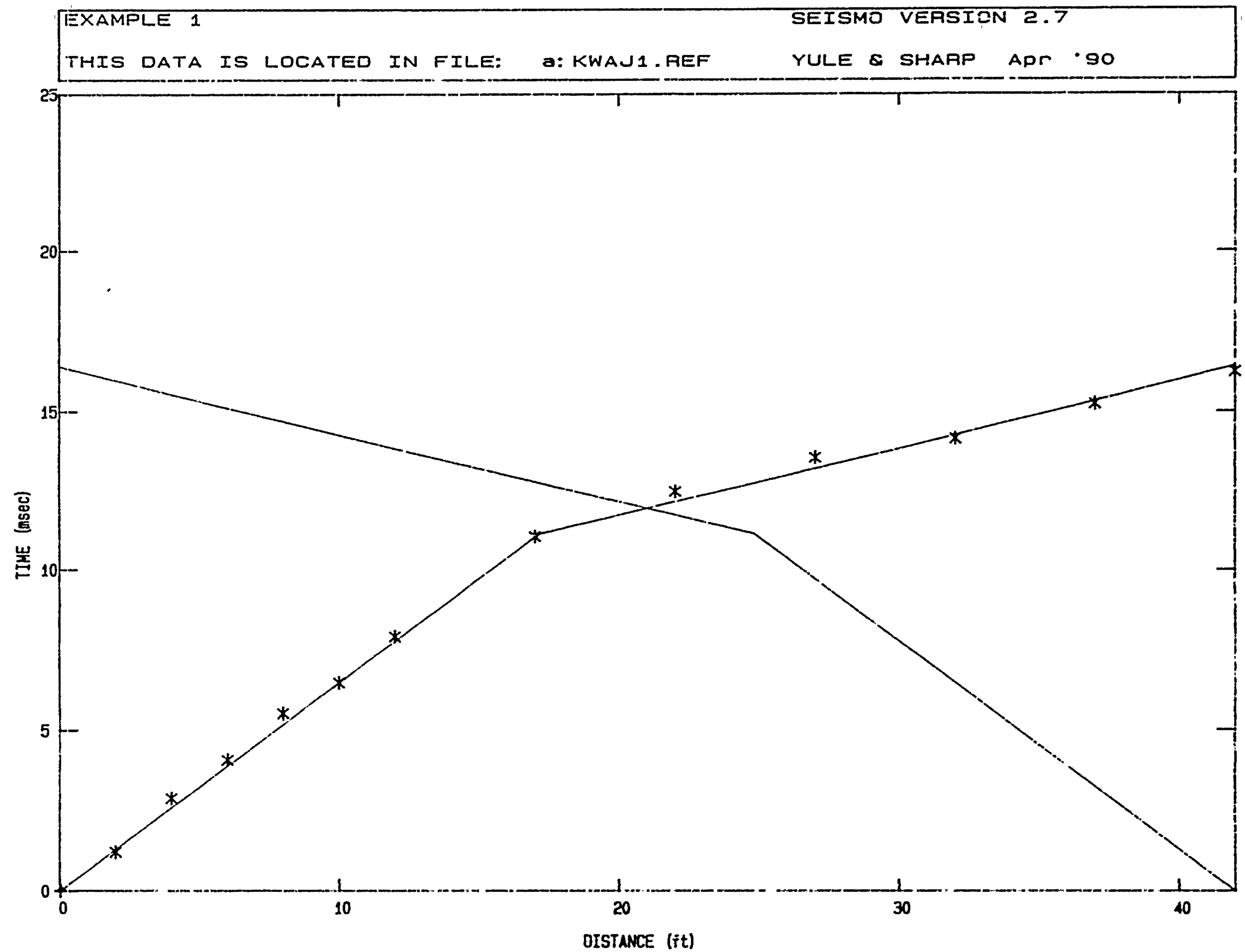


Figure 2. Working 5x7 inch plot for example 1.

kwaj1

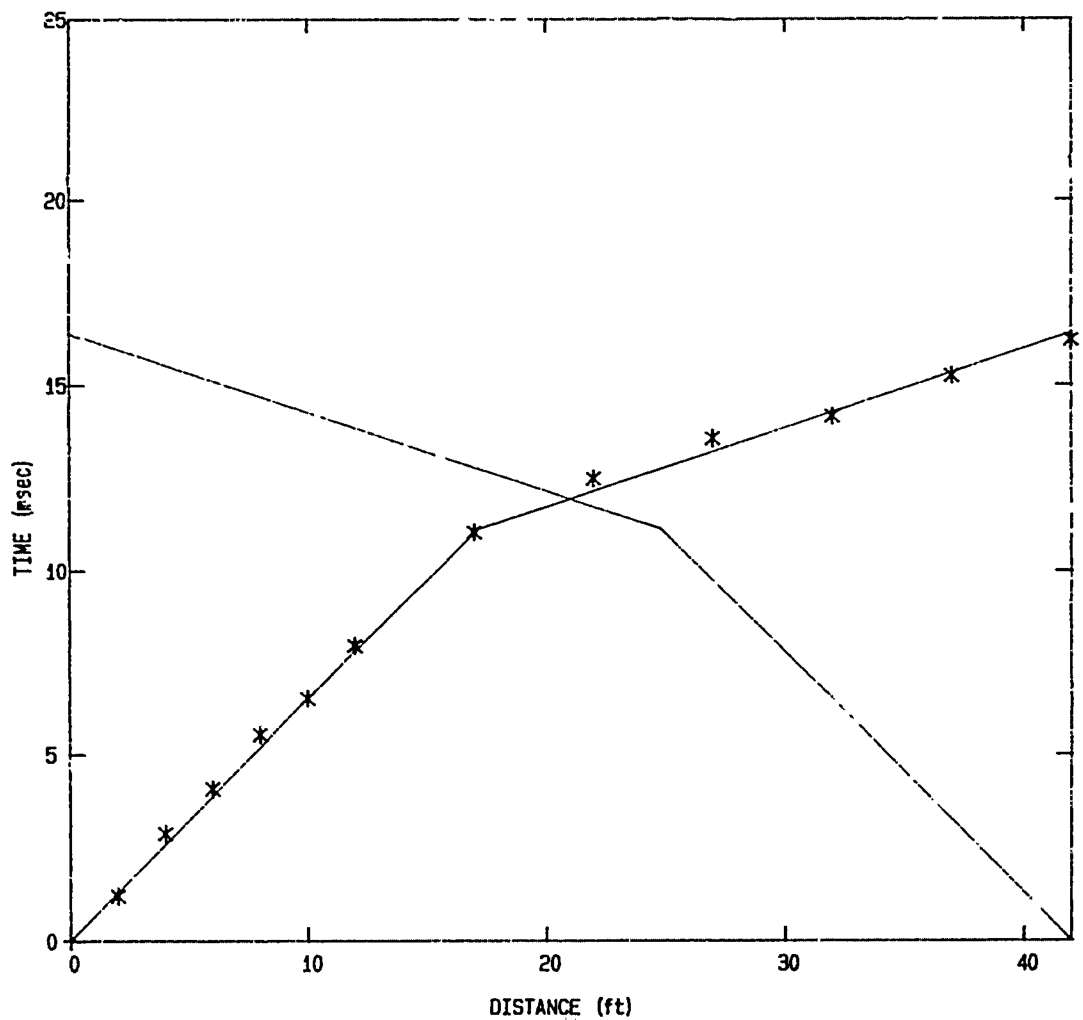
*** INPUT DATA ***

	FORWARD		REVERSE	
LAYER #	VEL ft/s	TIME msec	VEL ft/s	TIME msec
1	1543	0.0	1543	0.0
2	4721	7.5	4721	7.5

*** COMPUTED SEISMIC PROFILE ***

LAYER #	TRUE VEL ft/s	DEPTH FOR ft	DEPTH REV ft
1	1540		
2	4720	6.0	6.0

Figure 3. Printout of input data and calculated results for example 1.



EXAMPLE 1

**** INPUT DATA ****

layer #	forward vel ft/s	forward ti msec	reverse vel ft/s	reverse ti msec
1	1543	0	1543	0
2	4721	7.5	4721	7.6

**** COMPUTED PROFILE ****

Ground Surface

1540

6 6

4720

This layer extends to unknown depth

NOTE: All depths in ft
All velocities in ft/s

Figure 4. Final plate for example 1.

results. This in affect means that the layers can only be interpreted as being horizontal with no indication of dipping. The plot also contains the identifier, filename where data is located, program version number and authors.

4. Figures 3 and 4 contain the calculated results of the input data and model, with Figure 4 being the report ready presentation. The input data are velocities and intercept times for each layer, the calculated results are the true velocity for each layer and the depth to each interface. Notice that the input data for the reverse traverse has been made to equal that of the forward traverse, and that the calculated depth to interface for the forward and reverse end of the spread are the same. This is indicative of a single sided spread. Figure 4 contains the plot and the results, with the computed results presented as an idealized profile.

5. Example 2. The case presented as example 2 is shown in Figures 5-12. Figure 5 is a printout of the data located in a file named KWAJ12M.REF, and with the identifier kwaj12. The seismic refraction spread contained 12 geophones and extended, from shotpoint to shotpoint, 110 ft. In addition, there was a short line, 42 ft, run at the reverse end of the spread which contained 12 geophones and is referred to as the overburden line. This line had a shotpoint at one end only, geophones spaced 2 ft apart, and a distance from shotpoint to first geophone of 2 ft. This line was performed to better delineate the near surface layering. Doing an overburden spread is common practice, especially when the distance between geophones on the main spread are large. Too large a geophone spacing can result in missing the first layer if it is of a thickness less than the distance between the shotpoint and first geophone. In this case the overburden line data was added to the end of the file, it could also reside in a separate file and plotted on the plot using the overlay routine. This file also contains a model printed at the bottom of the page.

6. The 5x7 inch working plot of the data is presented in Figure 6. The overburden line can be seen plotted along with the main spread data at the far end of the spread. Notice that the overburden line in addition to the main spread gives nine points in the first layer on the reverse end as compared to two points for the first layer on the forward end. The file location and identifier for the spread is located at the top of the plot.

7. The results of the data for example two are presented

SEISMIC DATA SUMMARY

DATA FILE NAME : A:KWAJ12M.REF
DATA IDENTIFICATION : kwaj12
THERE ARE : 12 FORWARD POINTS 24 REVERSE POINTS
LINE LENGTH : 110 ft

*** FORWARD POINTS ***		*** REVERSE POINTS ***	
Distance ft	Time msec	Distance ft	Time msec
5.0	4.3	5.0	2.9
10.0	7.9	10.0	6.2
20.0	10.3	20.0	12.2
30.0	13.2	30.0	14.2
40.0	14.9	40.0	16.1
50.0	17.0	50.0	17.8
60.0	19.0	60.0	19.7
70.0	20.9	70.0	20.9
80.0	22.3	80.0	22.8
90.0	24.2	90.0	24.5
100.0	25.9	100.0	25.2
105.0	26.9	105.0	26.2
		2.0	1.2
		4.0	2.9
		6.0	4.1
		8.0	5.5
		10.0	6.5
		12.0	7.9
		17.0	11.0
		22.0	12.5
		27.0	13.6
		32.0	14.2
		37.0	15.2
		42.0	16.2

END OF DATA

MODEL SAVED WITH DATA

*** FORWARD MODEL ***		*** REVERSE MODEL ***	
Velocity ft/sec	Intercept msec	Velocity ft/sec	Intercept msec
1347	0.0	1586	0.0
5095	7.1	5202	8.2
6217	9.7	6725	10.9

Figure 5. Printout of time-distance data for example 2.

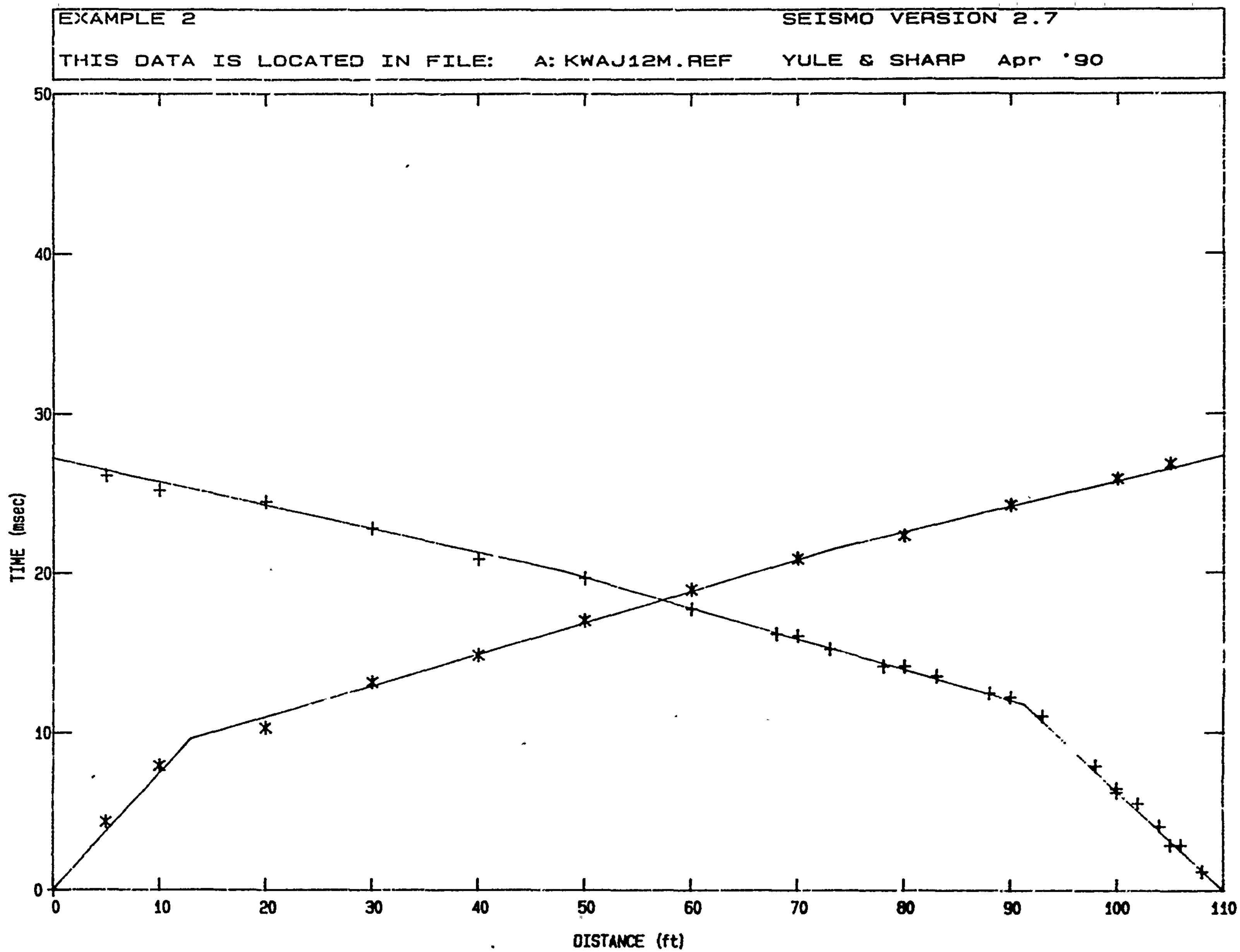


Figure 6. Working 5x7 inch plot of example 2.

kwaj12

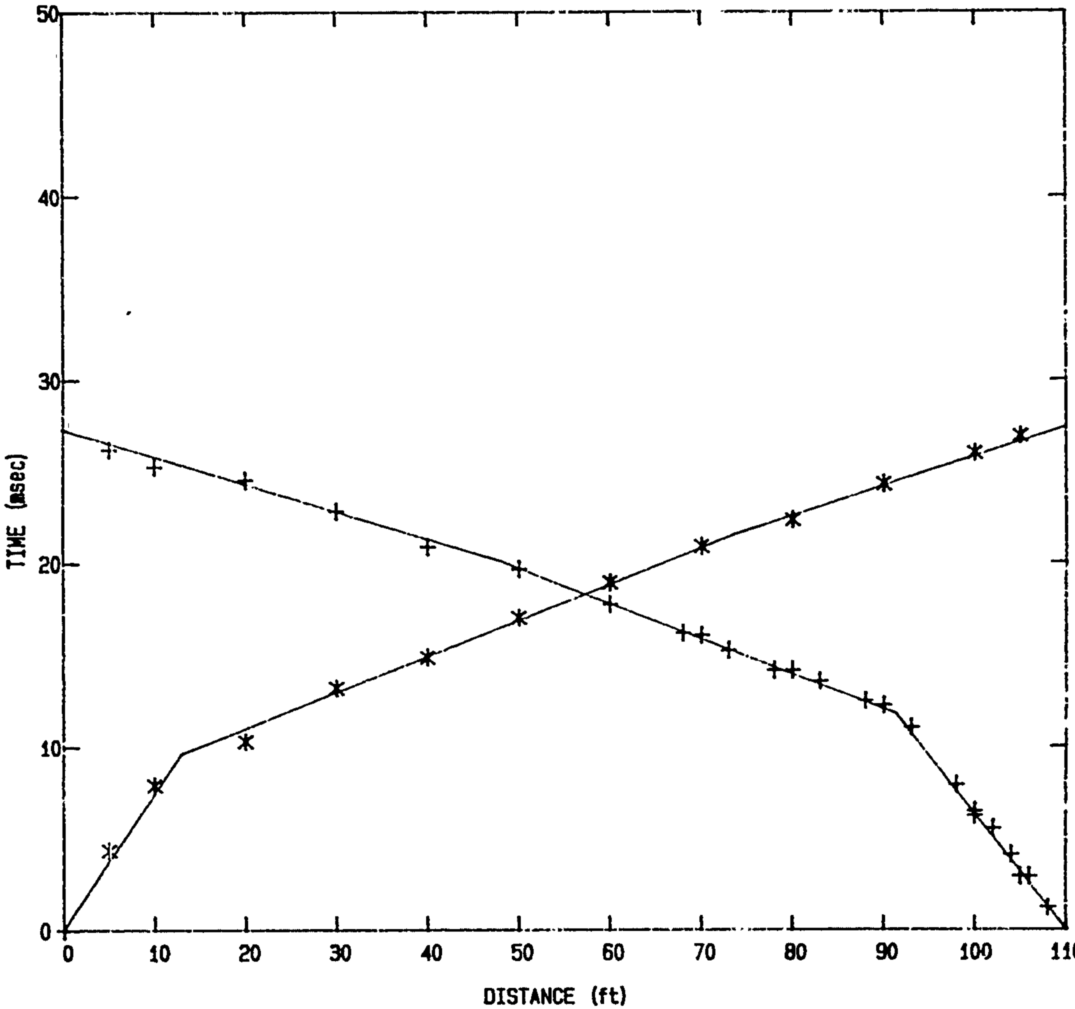
*** INPUT DATA ***

LAYER #	FORWARD VEL ft/s	FORWARD TIME msec	REVERSE VEL ft/s	REVERSE TIME msec
1	1347	0.0	1586	0.0
2	5095	7.1	5202	8.2
3	6217	9.7	6725	10.9

*** COMPUTED SEISMIC PROFILE ***

LAYER #	TRUE VEL ft/s	DEPTH FOR ft	DEPTH REV ft
1	1470		
2	5150	5.5	6.5
3	6460	16.0	17.0

Figure 7. Printout of input and calculated data for example 2.



EXAMPLE 2

**** INPUT DATA ****

layer #	forward vel ft/s	forward ti msec	reverse vel ft/s	reverse ti msec
1	1347	0	1586	0
2	5095	7.1	5202	8.2
3	6217	9.7	6725	10.9

**** COMPUTED PROFILE ****

Ground Surface

1470

5.5 ———— 6.5

5150

16 ———— 17

8460

This layer extends to unknown depth

NOTE: All depths in ft
All velocities in ft/s

Figure 8. Final plate for example 2.

SEISMIC DATA SUMMARY

DATA FILE NAME : kwajmetr.ref
DATA IDENTIFICATION : kwaj12
THERE ARE : 12 FORWARD POINTS 24 REVERSE POINTS
LINE LENGTH : 34 m

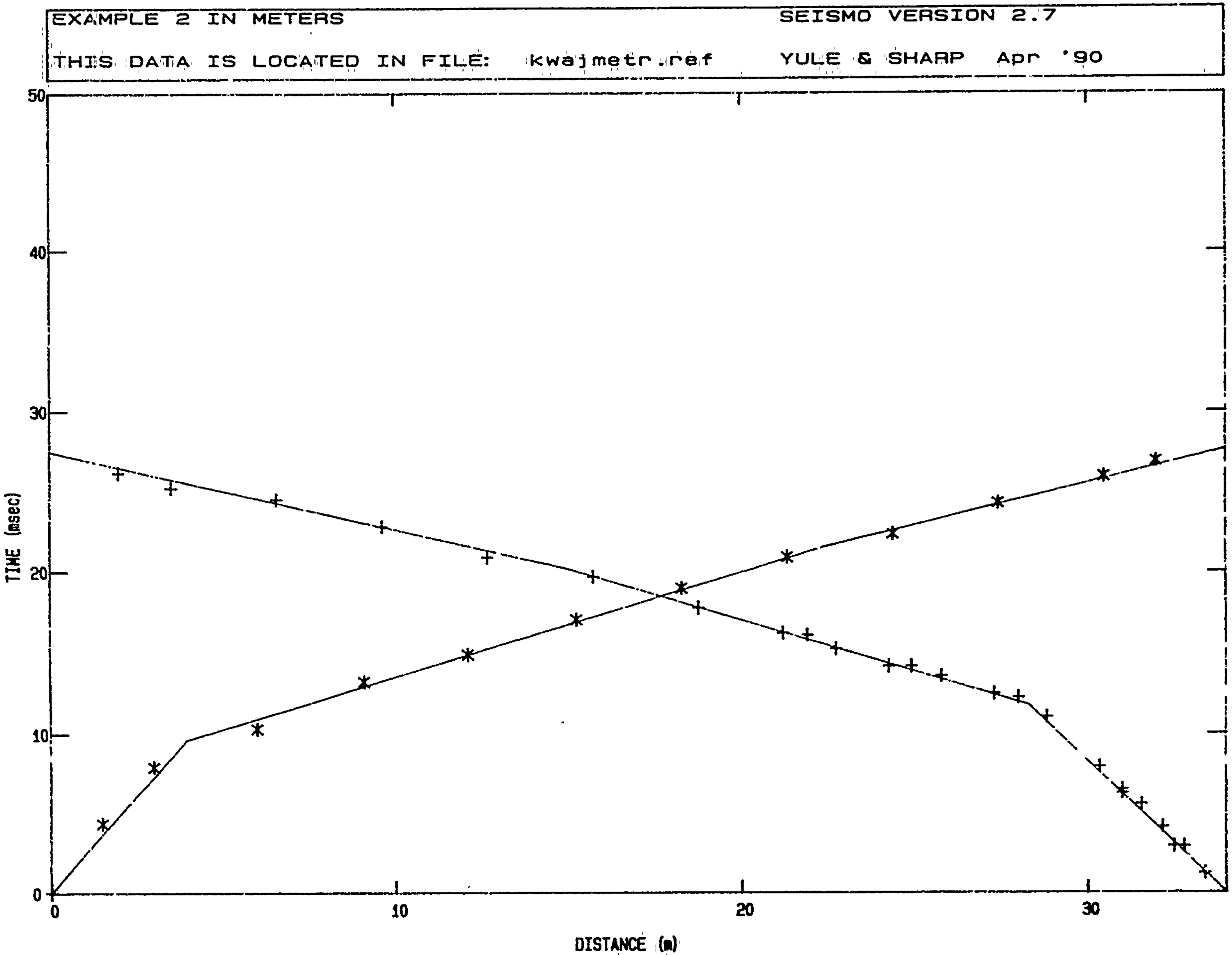
*** FORWARD POINTS ***		*** REVERSE POINTS ***	
Distance m	Time msec	Distance m	Time msec
1.5	4.3	1.5	2.9
3.0	7.9	3.0	6.2
6.0	10.3	6.0	12.2
9.1	13.2	9.1	14.2
12.1	14.9	12.1	16.1
15.2	17.0	15.2	17.8
18.3	19.0	18.3	19.7
21.3	20.9	21.3	20.9
24.4	22.3	24.4	22.8
27.4	24.2	27.4	24.5
30.5	25.9	30.5	25.2
32.0	26.9	32.0	26.2
		0.6	1.2
		1.2	2.9
		1.8	4.1
		2.4	5.5
		3.0	6.5
		3.7	7.9
		5.2	11.0
		6.7	12.5
		8.2	13.6
		9.8	14.2
		11.3	15.2
		12.8	16.2

END OF DATA

MODEL SAVED WITH DATA

*** FORWARD MODEL ***		*** REVERSE MODEL ***	
Velocity m /sec	Intercept msec	Velocity m /sec	Intercept msec
411	0.0	483	0.0
1553	7.1	1586	8.2
1895	9.7	2050	10.9

Figure 9. Printout of time-distance data for example 2 in meters.



Fgiure 10. Working 5x7 inch plot of example 2 in meters.

kwaj12

*** INPUT DATA ***

	FORWARD		REVERSE	
LAYER #	VEL m /s	TIME msec	VEL m /s	TIME msec
1	411	0.0	483	0.0
2	1553	7.1	1586	8.2
3	1895	9.7	2050	10.9

*** COMPUTED SEISMIC PROFILE ***

LAYER #	TRUE VEL m /s	DEPTH FOR m	DEPTH REV m
1	450		
2	1570	1.5	2.0
3	1970	5.0	5.5

Figure 11. Prinout of results for example 2 in meters.

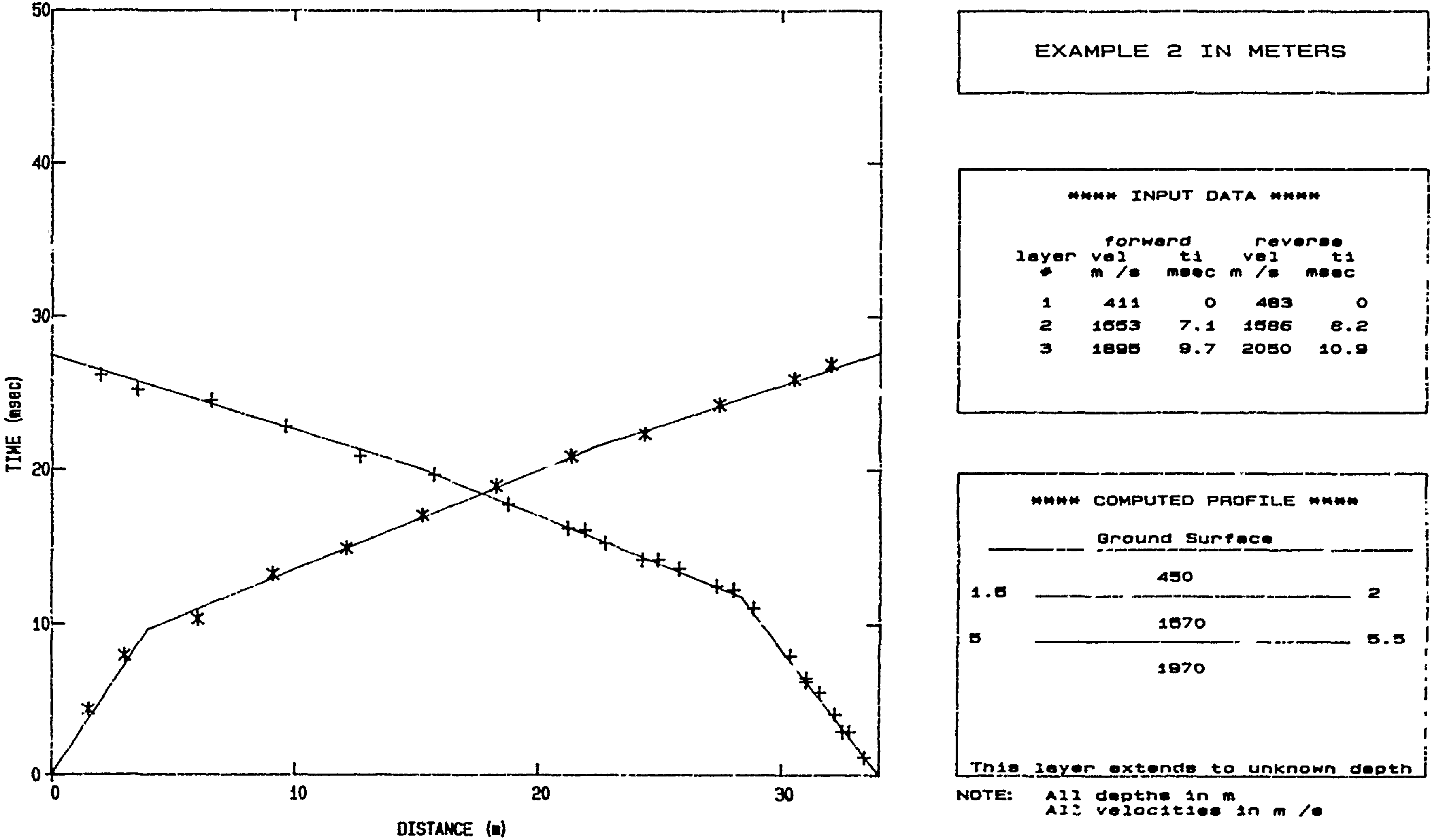


Figure 12. Final plate of example 2 in meters.

in Figures 7 and 8. This particular case revealed a three layer system for the site, with the last layer extending to an unknown depth, limited by the spread length. Also notice that the layers are dipping downward (positive angle) from distance equal 0 ft to distance equal 110 ft. This is shown in the idealized profile.

8. This case has been repeated in Figures 9-12 with the units changed to meters as opposed to feet. The case is the same as described above, except that the printouts have changed from units of ft and ft/sec to m and m/sec, and all distances are in meters.

9. Example 3. The case presented as example 3 is shown in Figures 13-17. Figure 13 is a printout of the data as reduced from the field. The data are located in a file in directory QB4 named WSB4R8.REF with the identifier wsb4r8. The spread had 24 geophones spaced 2 ft apart and a shotpoint at each end spaced 2 ft from the first geophone forward and reverse respectively. The total length of the spread was 50 ft. There was a model saved with the data, and it is printed at the bottom of Figure 13. This case is presented to show how the terrain/shotpoint correction routine functions.

10. The 5x7 inch working plot of the data is presented in Figure 14. It can be clearly seen that the data are affected by terrain. At a distance of 10 ft from the forward shotpoint, the arrival times suddenly drop off from the strait line segment placed through the data. This same effect can be seen in the case of the reverse data. The arrival times are all less than would be expected, which indicates that they must have either passed through a fast zone or had a shorter travel path. In this case the effects of terrain are producing shorter travel paths (a dip in the topography) and hence the reduction in travel times. Therefore, the data were terrain corrected in the program to remove the effects of topography on the data set. There was no correction made for shotpoint depth since the source was placed at the surface, however, that could also be included in the correction.

11. The results of the terrain corrected data are presented in Figures 15-17. The printout of the terrain corrected data is given in Figure 15. The printout contains the usual file location, line information, data, and model. The data are distances from source to each geophone (Dist), original uncorrected time (UTime), corrected time (CTime), elevations entered (Cor), and velocities used in correction routine (CVel).

SEISMIC DATA SUMMARY

DATA FILE NAME : \QB4\WSB4R8.REF
DATA IDENTIFICATION : wsb4r8
THERE ARE : 24 FORWARD POINTS 24 REVERSE POINTS
LINE LENGTH : 50 ft

*** FORWARD POINTS ***		*** REVERSE POINTS ***	
Distance ft	Time msec	Distance ft	Time msec
2.0	3.0	2.0	4.0
4.0	4.5	4.0	5.0
6.0	6.0	6.0	6.8
8.0	7.0	8.0	7.5
10.0	8.0	10.0	8.5
12.0	7.5	12.0	9.0
14.0	8.0	14.0	10.0
16.0	10.0	16.0	10.5
18.0	11.0	18.0	11.5
20.0	12.5	20.0	12.5
22.0	14.0	22.0	13.0
24.0	16.5	24.0	14.5
26.0	16.0	26.0	16.5
28.0	17.5	28.0	18.0
30.0	18.5	30.0	19.5
32.0	21.5	32.0	20.5
34.0	22.0	34.0	22.0
36.0	23.0	36.0	23.0
38.0	24.0	38.0	24.0
40.0	26.0	40.0	25.0
42.0	27.5	42.0	26.0
44.0	28.0	44.0	28.0
46.0	30.0	46.0	29.0
48.0	32.0	48.0	31.0

END OF DATA

MODEL SAVED WITH DATA

*** FORWARD MODEL ***		*** REVERSE MODEL ***	
Velocity ft/sec	Intercept msec	Velocity ft/sec	Intercept msec
688	0.0	542	0.0
1694	2.4	1776	2.6

Figure 13. Printout of time-distance data for example 3.

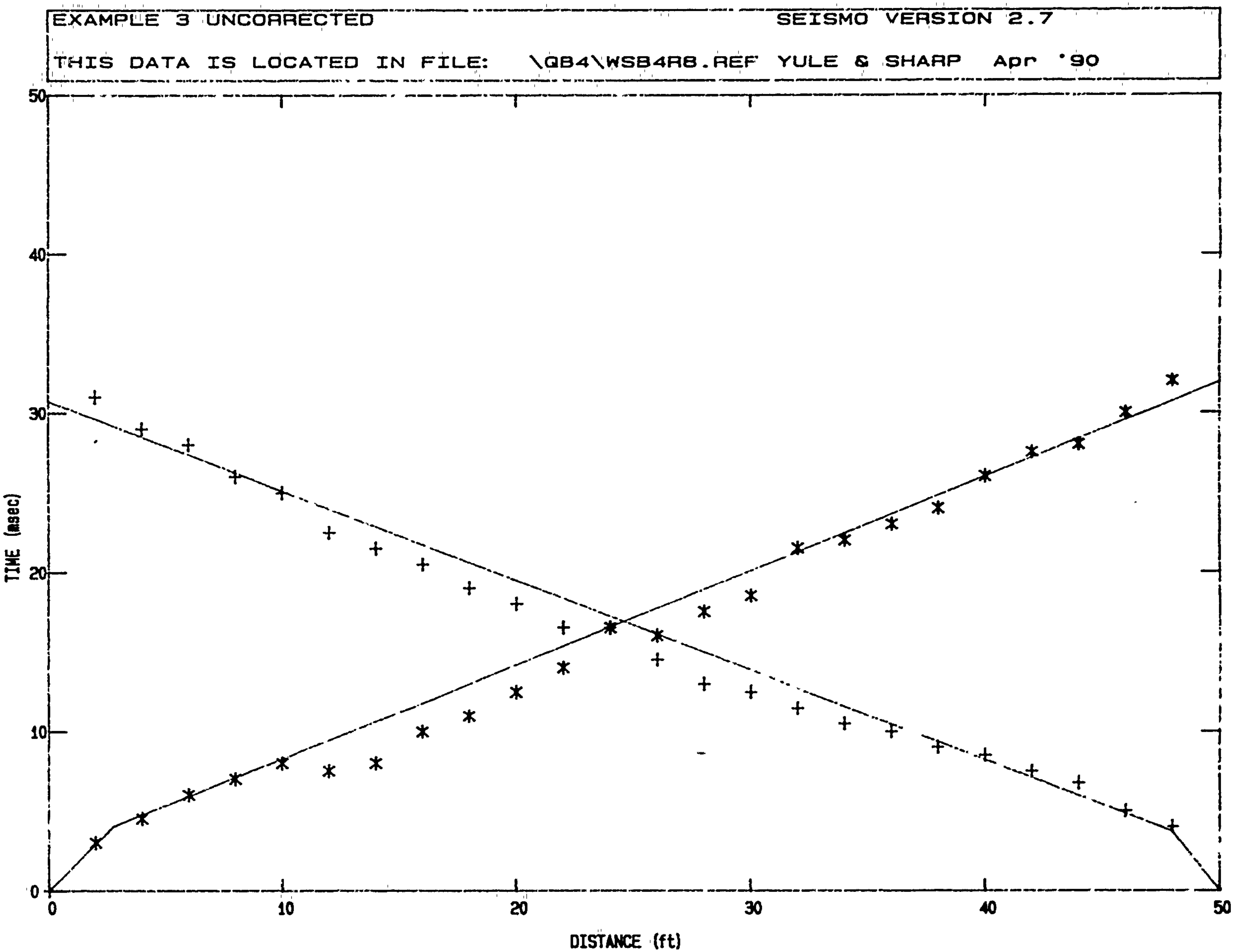


Figure 14. Working 5x7 inch plot of example 3 uncorrected data.

SEISMIC DATA SUMMARY

DATA FILE NAME : \QB4\WSB4R8.REF
DATA IDENTIFICATION : wsb4r8
THERE ARE : 24 FORWARD POINTS 24 REVERSE POINTS
LINE LENGTH : 50 ft

*** FORWARD POINTS ***					*** REVERSE POINTS ***				
Dist ft	UTime msec	CTime msec	Cor ft	CVel ft/sec	Dist ft	UTime msec	CTime msec	Cor ft	CVel ft/sec
2.0	3.0	3.0	0.0	615.0	2.0	4.0	4.0	0.0	615.0
4.0	4.5	4.5	0.0	615.0	4.0	5.0	5.0	0.0	615.0
6.0	6.0	6.0	0.0	615.0	6.0	6.8	6.8	0.0	615.0
8.0	7.0	7.0	0.0	615.0	8.0	7.5	7.5	0.0	615.0
10.0	8.0	8.0	0.0	615.0	10.0	8.5	8.5	0.0	615.0
12.0	7.5	9.8	1.5	615.0	12.0	9.0	10.0	0.0	615.0
14.0	8.0	10.3	1.5	615.0	14.0	10.0	11.0	0.0	615.0
16.0	10.0	12.3	1.5	615.0	16.0	10.5	11.5	0.0	615.0
18.0	11.0	13.3	1.5	615.0	18.0	11.5	12.5	0.0	615.0
20.0	12.5	14.8	1.5	615.0	20.0	12.5	14.8	1.5	615.0
22.0	14.0	16.3	1.5	615.0	22.0	13.0	15.3	1.5	615.0
24.0	16.5	16.5	0.0	615.0	24.0	14.5	16.8	1.5	615.0
26.0	16.0	18.3	1.5	615.0	26.0	16.5	16.5	0.0	615.0
28.0	17.5	19.8	1.5	615.0	28.0	18.0	18.3	1.5	615.0
30.0	18.5	20.8	1.5	615.0	30.0	19.5	19.8	1.5	615.0
32.0	21.5	21.5	0.0	615.0	32.0	20.5	20.8	1.5	615.0
34.0	22.0	22.0	0.0	615.0	34.0	22.0	22.3	1.5	615.0
36.0	23.0	23.0	0.0	615.0	36.0	23.0	23.3	1.5	615.0
38.0	24.0	24.0	0.0	615.0	38.0	24.0	24.3	1.5	615.0
40.0	26.0	26.0	0.0	615.0	40.0	25.0	25.0	0.0	615.0
42.0	27.5	27.5	0.0	615.0	42.0	26.0	26.0	0.0	615.0
44.0	28.0	28.0	0.0	615.0	44.0	28.0	28.0	0.0	615.0
46.0	30.0	30.0	0.0	615.0	46.0	29.0	29.0	0.0	615.0
48.0	32.0	32.0	0.0	615.0	48.0	31.0	30.0	0.0	615.0

END OF DATA

MODEL SAVED WITH DATA

*** FORWARD MODEL ***		*** REVERSE MODEL ***	
Velocity ft/sec	Intercept msec	Velocity ft/sec	Intercept msec
688	0.0	542	0.0
1694	2.4	1776	2.6

Figure 15. Printout of corrected time-distance data example 3.

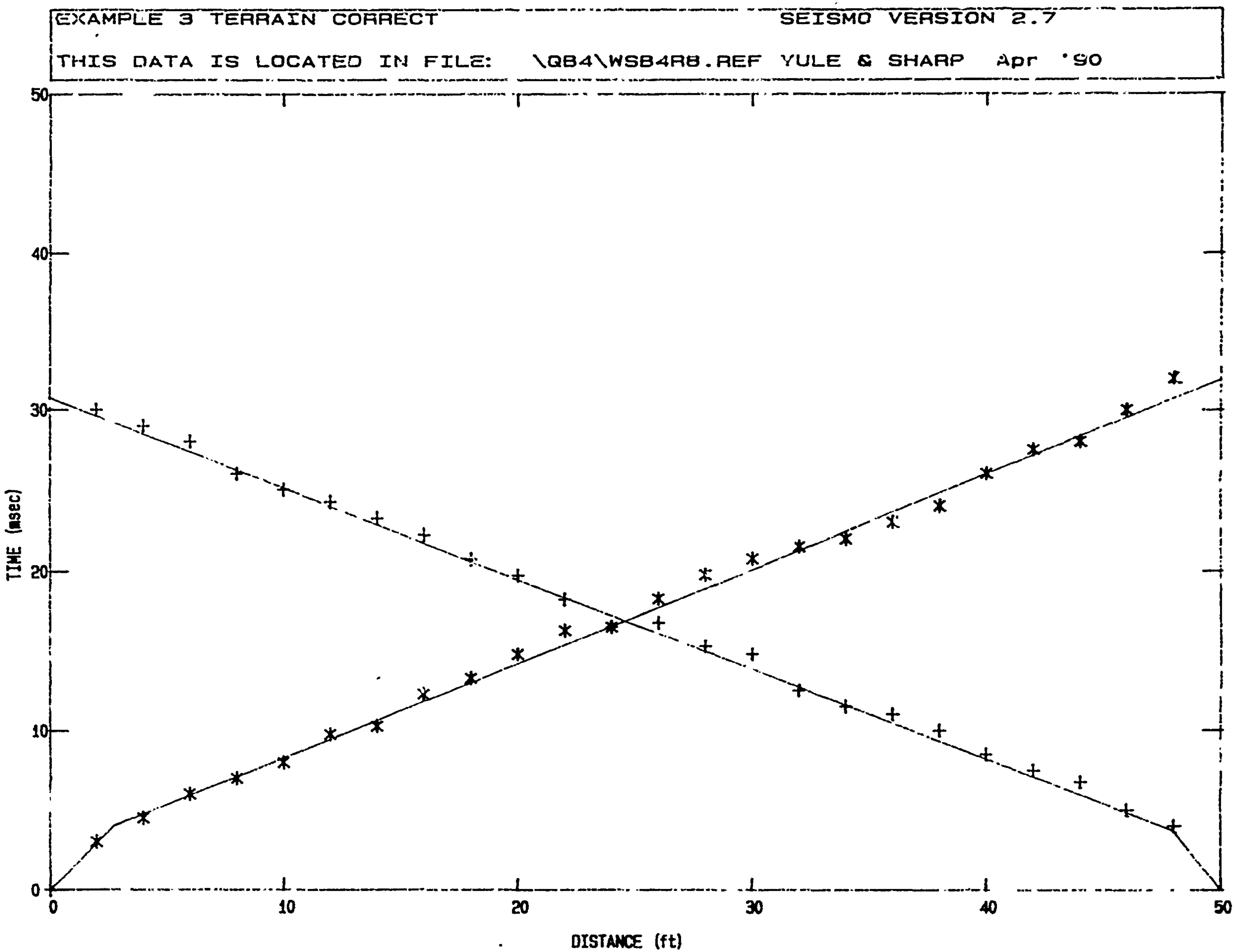


Figure 16. Working 5x7 inch plot of corrected data example 3.

wsb4r8

*** INPUT DATA ***

LAYER #	FORWARD VEL ft/s	FORWARD TIME msec	REVERSE VEL ft/s	REVERSE TIME msec
1	688	0.0	542	0.0
2	1694	2.4	1776	2.6

*** COMPUTED SEISMIC PROFILE ***

LAYER #	TRUE VEL ft/s	DEPTH FOR ft	DEPTH REV ft
1	620		
2	1730	1.0	1.0

Figure 17. Printout of results from example 3.

Notice that the geophones from distance 12 ft to distance 30 ft (forward) have all been corrected to a common datum plane, which was selected to be the elevation of the shotpoint. In other words, there was a dip in the line at this location and the geophones were elevated to the new location selected as the datum plane by adding 1.5 ft to them. The program takes this 1.5 ft and the velocity of 615 ft/sec to calculate the correction in msec to be added or subtracted from the data. Figure 16 is a plot of the data with the corrections applied. Comparing this plot with that in Figure 14, a marked difference in the arrival times can be seen. Figure 17 is a printout of the calculated results for this model.